Sound Science: Synthesizing Ecological and Socio-economic Information about the Puget Sound Ecosystem

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Contents

4. **The Future of Puget Sound** (*To be completed*) *This section is intended to consist of a series of papers on issues that have surfaced as primary drivers of change to the future of the Puget Sound ecosystem. Each paper would be completed by one or more scientists from the relevant field of expertise, and would be approximately 5 6 pages long.*
   - 4.1 Climate Change and the Puget Sound
   - 4.2 Forming and Maintaining Habitats:
   - 4.3 Species and their Interactions: Top Down and Bottom Up Changes
   - 4.4 Interactions between Natural and Human Systems in Puget Sound
   - 4.5 Human Health and Well-being
   - 4.6 Integrating the Sciences: Natural and Social Science Support for Decision-Making

5. **Key Findings**

Section 1: Problems and Opportunities for Puget Sound

1.1 Puget Sound: Enduring Beauty and Growing Distress

Puget Sound (Figure 1-1) provides a home to over 3.8 million human residents, anxious to preserve the natural splendor and economic opportunity that has drawn and sustained them. Despite the striking visual beauty of the Puget Sound region, it is clear that this ecosystem has incurred many injuries. Over 40 species of birds, mammals, fishes, plants and invertebrates are currently listed as threatened, endangered, or as candidates for state and federal endangered species lists. Each of these species plays a unique and highly connected role within the Puget Sound ecosystem. Moreover, some of these listed species, such as Puget Sound Chinook salmon (*Oncorhynchus tshawytscha)* and killer whales (*Orcinus orca)*, are icons of the Pacific Northwest which have been celebrated in art, culture and tradition for many centuries.

Threatened and endangered species listings are not the only indicators of decline in the health of the Puget Sound ecosystem. Several important documents including the State of the Sound Report (PSAT, 2005), the Puget Sound Update (PSWQAT, 2002; 2006 edition in progress), and the Puget Sound Salmon Recovery Plan (Shared Strategy, 2005) report that:

Pollution in Puget Sound has left a toxic legacy, and past and present contaminants remain a serious problem for the Puget Sound food web.

- Levels of Polychlorinated Biphenyls (PCBs) and Polycyclic Aromatic Hydrocarbons (PAHs) in several species of fish and shellfish have triggered consumption advisories.
- Long term monitoring indicates that PAH levels have increased, but metals such as arsenic, mercury and lead have declined.
- Although cleanup activities have resulted in substantial improvement, approximately 5,700 submerged acres of highly contaminated sediments remain in the Sound. Intermediate and highly degraded habitats occur largely in harbors and adjacent to urban centers.
- From 1997 to 2004, the number of areas where edible shellfish grow that were placed on the threatened list doubled due to pollution. However, monitoring and cleanup efforts have resulted in a net upgrade of 7,500 acres of commercial shellfish areas.

Habitat loss and modification is widespread throughout Puget Sound.

- An 1885 survey estimated that there were 267 km^2 of tidal marsh and swamplands bordering Puget Sound. A comparison approximately 100 years later indicated that 54.6 km^2 remained -- a decline of 80% Sound-wide.
- Approximately one-third of the Puget Sound shoreline has been modified with bulkheads, docks, revetments or other armoring affecting the transport and replenishment of sediment to beaches or other nearshore habitats.
- Freshwater habitat for Puget Sound Chinook salmon rearing has declined by over 1,000 km, a loss of approximately 25% of historic capacity overall.

- Impervious land cover in the Puget Sound basin increased by more than 7% in an 8-year period in the 1990s.
- In addition to the threatened species listings, populations of many species of forage fish and marine birds have declined dramatically since the 1970s.

The human population in the Puget Sound and Georgia Basin region is expected to grow by two to three million new residents within the next 20 years, potentially putting severe stresses on the ecosystem services we have come to value. Without concerted action to protect the structure and function of the Puget Sound ecosystem, the resilience of the system will decline and we will be less able to derive benefits from the ecosystem. Additionally, it is essential to broaden our tracking of individual indicators of ecosystem health and include evaluation of how global, chemical and physical processes are linked to human values and actions, thereby driving the productivity of the Puget Sound ecosystem as a whole.

[Graphics note: Will insert the graph of projected human population increase in PS and GB here.]

1.2 National Calls for Ecosystem-Based Management

Observable, widespread declines in the status of species, habitats, and functions in marine waters and terrestrial landscapes have led to calls for ecosystem-scale management as a strategy to heal our watersheds and coastal oceans (Pew 2003, USCOP 2004). At the core of a system-wide approach to natural resource management is the importance of considering the factors that drive human behaviors and choices, as well as the potential consequences of our actions on the natural system. Clearly the implementation of an ecosystem approach to natural resource management in our coastal communities will require an understanding of the complexities of terrestrial, estuarine and marine ecosystems along with insight on how humans fit into the system as consumers, competitors and producers.

Other regions of the United States have experienced significant natural resource challenges on an ecosystem scale, including the Chesapeake Bay, the Everglades, Louisiana delta, Great Lakes and the Sacramento/San Francisco delta/bay area. Major modifications to the structure and function of these ecosystems have reduced the services they can provide, and vast sums of money and several human lifetimes will be required to remediate the problems. Puget Sound still presents a unique opportunity to take proactive measures to recover and maintain a healthy and viable ecosystem before degradation becomes widespread and irreversible.

Coastal waters are one of the nation's greatest assets, yet they are being bombarded with pollutants from a variety of sources. While progress has been made in reducing point sources of pollution, non-point source pollution has increased and is the primary cause of nutrient enrichment, hypoxia, harmful algal blooms, toxic contaminants, and other problems that plague coastal waters. Non-point source pollution occurs when rainfall and snowmelt wash pollutants such as fertilizers, pesticides, bacteria, viruses, pet waste, sediments, oil, chemicals, and litter into our rivers and coastal waters… Our failure to manage the human activities that affect the nation's oceans is compromising their ecological integrity, diminishing our ability to fully realize their potential, costing us jobs and revenue, threatening human health, and putting our future at risk.

– **Executive Summary, An Ocean Blueprint for the 21st Century (2004)**

U.S. COMMISSION ON
OCEAN POLICY

1.3 Opportunities for Ecosystem-Based Management in Puget Sound

Constructive efforts to protect and restore areas of Puget Sound have been underway for many years. A number of studies have contributed to the body of scientific information specific to Puget Sound ecosystem habitats, species and processes (box ___). These efforts tie closely to the national call for ecosystem based management to pull together the fractionated management of our oceans and waterways that is prevalent in many parts of the country. Ecosystem based management is an opportunity for Puget Sound to look at the broader impact of human actions on ecosystem function, how changes in ecosystem function affects what benefits we can reap from the natural system, and to grapple with the potential tradeoffs inherent in the natural and human systems in Puget Sound.

Governor Christine Gregoire formed the Puget Sound Partnership in late 2005 to engage citizens, businesses, watershed groups, scientists and leaders from tribal, local, state and federal governments in developing recommendations for what actions are needed to,

> *Preserve the health, goods and services needed by the year 2020 to ensure that the Puget Sound's marine and freshwaters will be able to support healthy populations of the native species, as well as water quality and quantity to support both human needs and ecosystem functions.*

The Puget Sound Partnership presents an immediate opportunity to apply the principles encouraged by the national ocean commissions in setting goals and actions for Puget Sound. In developing this document, Puget Sound natural and social scientists have considered the Governor's charge with a series of broad questions for ecosystem management:

- What are the current processes that form and sustain habitats, species and other ecosystem services?
- How have ecosystem services in Puget Sound changed over the past two centuries?
- What are the drivers of ecosystem change in Puget Sound?
- How might Puget Sound ecosystems respond in the future to changing conditions and actions, and what are some of the uncertainties?
- What options exist to consider linkages and tradeoffs so as to manage the ecosystem sustainably?

Ultimately, the purpose of Sound Science is to help inform natural resource policies in Puget Sound through the application of broadly-based scientific knowledge at the ecosystem level. The Sound Science document has been prepared with input from the Puget Sound scientific community in order to characterize the elements, processes and linkages of the Sound ecosystem as a whole; highlight major issues affecting the future; and identify some of the key gaps in current scientific understanding that hinder our ability to manage Puget Sound sustainably.

Sidebar:

A few of the major reports and plans recently produced for Puget Sound include…

- ***State of the Sound 2004.*** *(Puget Sound Action Team (PSAT), 2005) This report on the health of Puget Sound focuses on 15 environmental indicators reflecting the condition of the Sound's water and submerged lands, habitats, and species, and the threats to these resources. www.psat.wa.gov*

- ***Puget Sound Conservation and Management Plan 2005-2006.*** *(PSAT, 2005) Action plan covering high priority activities for Puget Sound, including:*
  1. Cleanup contaminated sites and sediments
  2. Prevent toxic contamination
  3. Prevent harm from stormwater runoff
  4. Prevent nutrient and pathogen pollution (Special Focus Area: Hood Canal)
  5. Protect functioning nearshore and freshwater habitats
  6. Restore degraded nearshore and freshwater habitats
  7. Conserve and recover species at risk
  8. Prepare for and adapt Puget Sound efforts to a changing climate.

- ***Puget Sound Update: Report of the Puget Sound Assessment and Monitoring Program.*** *The PSAMP was initiated by the State of Washington in 1988 to integrate environmental quality assessments by local, state and federal agencies in Puget Sound. Coordinated by the Puget Sound Action Team, a technical report is published every few years. The next publication of this "Puget Sound Update" is anticipated in the Fall of 2006. Previous updates are available at www.psat.wa.gov.*

- ***Puget Sound Nearshore Ecosystem and Restoration Program:*** *PSNERP was formally initiated in September 2001 as a joint study by the U.S. Army Corps of Engineers and the State of Washington Department of Fish and Wildlife to evaluate significant ecosystem degradation in the Puget Sound Basin and formulate solutions with local partners. Additional organizations joined the program and created the Puget Sound Nearshore Partnership. Several technical reports were published by the Partnership in 2004, including, "Guiding Restoration Principles," Guidance for Protection and Restoration of the Nearshore Ecosystems of Puget Sound," and "Application of the 'Best Available Science' in Ecosystem Restoration: Lessons Learned from Large-Scale Restoration Project Efforts in the USA." These and other materials are available at http://pugetsoundnearshore.org.*

- ***Georgia Basin-Puget Sound Ecosystem Indicators Report****. (Environment Canada, US Environmental Protection Agency, PSAT; Spring 2002): Report examining selective aspects of the state of the environment in the bi-national transboundary region and indicators and trends for this shared ecosystem. www.env.gov.be.ca/spd/gbpsei/documents/gbpsei.pdf*

- ***Draft Puget Sound Salmon Recovery Plan*** *(Shared Strategy for Puget Sound, 2005). Draft recovery plan for threatened distinct population segments of Puget Sound Chinook and bull trout submitted to the National Marine Fisheries Service and US Fish and Wildlife Service. www.sharedsalmonstrategy.org*

- ***Preliminary Draft Conservation Plan for Southern Resident Killer Whales (Orcinus orca).*** *(National Marine Fisheries Service, 2005) www.nwr.noaa.gov/mmammals/whales/preliminkwconsplan.pdf*

The following reports were suggested as additions by reviewers:

- ***Uncertain Future: Climate Change and Its Effects on Puget Sound.*** *(Climate Impacts Group and University of Washington, 2005).* *http://www.psat.wa.gov/Publications/climate_change2005/climate_home.htm*

- ***Reports on the chemical contamination of Puget Sound Sediments*** *include:*
  "Temporal Monitoring of Puget Sound Sediments: Results of the Puget Sound Ambient Monitoring Program, 1989-2000 (Washington State Department of Ecology, 2005) *http://www.ecy.wa.gov/biblio/0503016.html*

  "Chemical Contamination, Acute Toxicity in Laboratory Tests and Benthic Impacts in Sediments of Puget Sound: A summary of results of the joint 1997-1999 Ecology/NOAA survey. (Washington State Department of Ecology, 2003). *http://www.ecy.wa.gov/biblio/0303049.html*

Section 2: Management of Puget Sound on an Ecosystem Scale

Marine and estuarine ecosystems like Puget Sound provide a full array of ecosystem products and services that humans enjoy. Goals for Puget Sound are often expressed in terms of clean beaches, healthy seafood, abundant wildlife, stable fisheries, or thriving coastal economies, but many ecosystem benefits are difficult to quantify. Furthermore, the ecosystem may provide one set of services, such as waste treatment, at the expense of other objectives, such as healthy seafood. Recent studies of the relationship of human values to ecosystem services are looking at ways to ensure that potential impacts throughout the entire ecosystem are considered when decisions are made, and that tradeoffs are explicitly recognized.

2.1 A Conceptual Framework

Changes in ecosystems due to natural and human causes result in changes in the goods and services provided by the ecosystem, thus affecting the well-being of humans and other species (Fig. 2-1). In order to measure progress towards achieving ecosystem goals, scientists often convert general goal statements into “ecosystem services” that can be more directly quantified and tracked over time (NRC 2004, MA 2005). The economic and social values ascribed to these ecosystem services, combined with ecological assessments of ecosystem function, can be used to evaluate management strategies and their potential effect on ecosystem productivity.

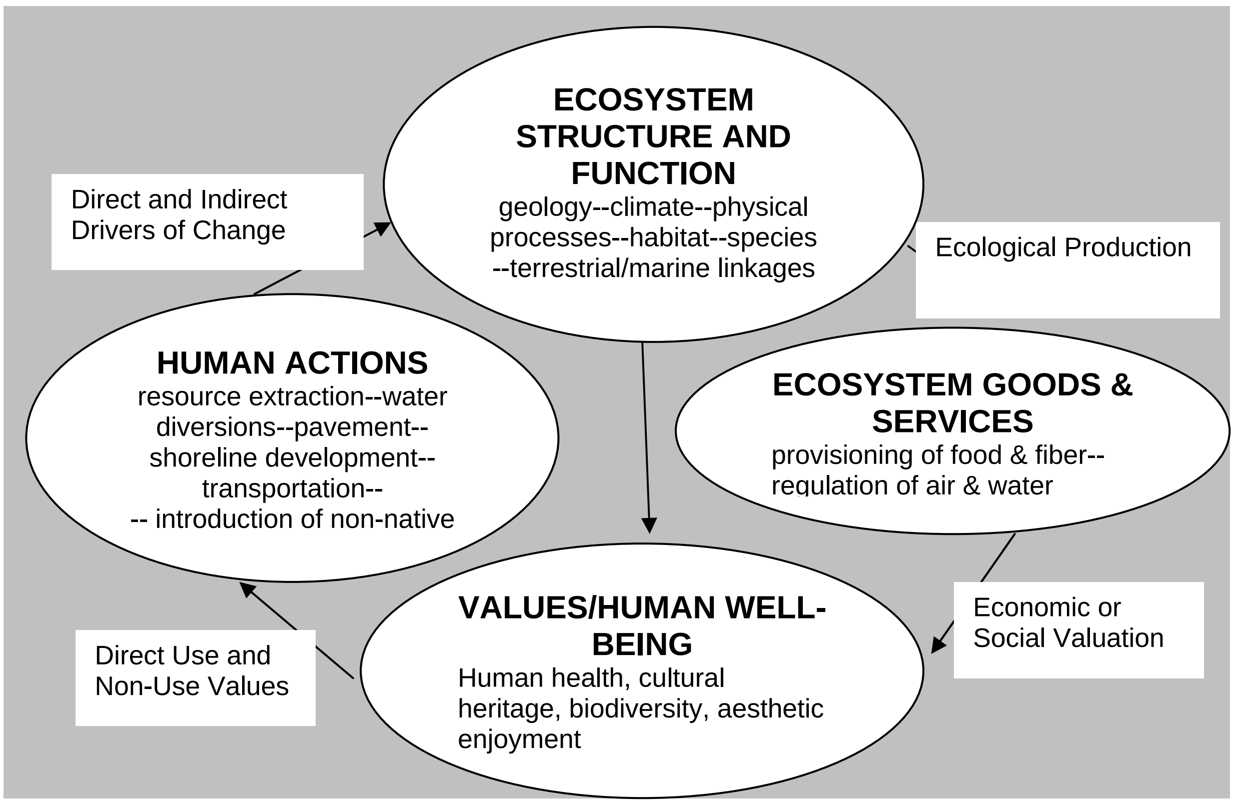

Figure 2-1: Relationship of Ecosystem Structure and Function and Human Well-Being (adapted from National Research Council 2004 and Millennium Ecosystem Assessment 2005).

2.2 Drivers of Ecosystem Change

Modifications to ecosystem services come through the primary drivers of ecosystem change and may be direct or indirect. Direct drivers of ecosystem change in Puget Sound include land use modification; species introduction or removals; technology adaptation; external inputs such as fertilizers, pharmaceuticals, and pesticides; harvest and resource consumption; climate change; and long-term natural drivers such as volcanoes, earthquakes or evolutionary changes in species (MA 2005). Indirect drivers of change to the Puget Sound ecosystem are factors such as patterns and rates of human population growth, local and global market behavior, governance and political frameworks, and cultural and religious beliefs and consumption choices (MA 2005).

2.3 Ecosystem Services

Ecosystem services are the “outputs” and experiences of ecosystems that benefit humans, and are generated by the structure and function of natural systems, often in combination with human activities.

Box __: Examples of Ecosystem Services from Puget Sound		
Provisioning Services	***Regulating Services***	***Cultural Services***
• Food and fiber (salmon, shellfish, pulp) • Fuel (wood, coal) • Fresh water • Genetic resources • Biochemicals, natural medicines, and pharmaceuticals (from marine invertebrates, medicinal plants) • Ornamental resources	• Air quality maintenance • Climate regulation • Water regulation • Erosion control • Water purification and waste treatment • Regulation of human diseases • Biological control • Pollination • Storm protection	• Recreation and ecotourism (whale watching, hiking) • Cultural diversity (tribal, rural & urban, Asian) • Spiritual and religious experiences • Knowledge systems (traditional and formal) • Education • Inspiration • Aesthetic experiences • Social relations • Sense of place • Cultural heritage values
***Supporting Services*:** Necessary for the production of all other ecosystem services. Examples include soil formation, primary production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.		
Source: MA (2003)		

The Millennium Ecosystem Assessment, a recent global effort to catalog and assess ecosystem status and functions, offers a useful classification scheme (Box __). Their classification includes four categories (MA, 2003).

- *Provisioning services* are the products obtained from ecosystems, such as food and fresh water. These services are typically measured in terms of biophysical production, such as tons of salmon landings.
- *Regulating services* are the benefits obtained from the regulation of ecosystem processes, such as nutrient assimilation. In the case of regulating services, as opposed to provisioning services, the level of “production” is generally not relevant. Instead, the condition of the service depends more on whether the ecosystem’s capability to regulate a particular service has been enhanced or diminished.
- *Cultural services* are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences. Recreation, ecotourism, spiritual and religious experiences, and a sense of place are all examples of this type of service. Perceptions of cultural services are more likely to differ among individuals and

communities than, say, perceptions of the importance of food production, and so they are harder to measure.

- *Supporting services* are those that are necessary for the production of all other ecosystem services. For example, humans do not consume low trophic level species like plankton, but these species support higher level species, some of which are consumed directly. Other examples of supporting services are primary production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

Puget Sound is home to commercial, recreational, and tribal ceremonial and subsistence fisheries for salmon and other species, as well as clam, oyster, crab, and other shellfish harvests. It provides regulating services as global as the carbon cycle, and as local as waste treatment through the uptake in estuaries of nutrients such as nitrogen and phosphorous. Puget Sound hosts myriad forms of recreation, including an active whale watching industry (Box __). Underlying all of these are Puget Sound's basic supporting services such as primary production and the provision of habitat for salmon, Orcas and other species. A similar set of services are provided by the freshwater ecosystems that are linked to Puget Sound (Postel and Carpenter, 1999).

Box ___: Valuing Ecosystem Services – Whale Watching in Puget Sound

Whale watching is an increasingly important tourism industry in the Puget Sound region, with an estimated 52,000 participants in commercial boat-based tours during 1998. The current whale watching industry in Puget Sound is estimated to contribute approximately $18.4 million annually and 205 jobs to the 19 counties adjacent to Puget Sound through direct and indirect expenditures related to the industry (IE 2006).

Whale watching would not be possible without the existence of the orca and other whales, thus it is tempting to ascribe the entire value of this activity to this ecological component. This ecosystem service, however, is the output of a combination of inputs, including human-made capital (boats) and fuel. Without any one of these components, this particular service would not be possible, making it problematic to assign the entire value of the service to any one input.

Managing Puget Sound with an ecosystem perspective may change the value ascribed to whale watching, but how this value changes over time may be complicated. If the orca population increases through management efforts, whale watching opportunities may also increase, increasing the value of the service. At the same time, any restrictions on the whale watching industry itself that are deemed necessary to protect the population would effectively decrease the value of the service in the short term. In addition, the value of the biodiversity (provisioning) and cultural services will be increased as whales increase.

2.4 Human Well-Being and Ecosystem Value

The values of ecosystem services can be categorized as “use values” such as direct consumption or use, or as “non-use values” (such as the value of leaving a legacy of biodiversity). These values in turn motivate actions that may produce effects that feed back to the ecosystem’s structure and function. Although the majority of values attached to ecosystem services are economic, they are not just market values but can be any service that contributes to the satisfaction of human wants. In building an ecosystem management framework from the conceptual model for Puget Sound (Figure 2-1), it is important to consider the context of an integrated, dynamic system in which humans play the part of both drivers and beneficiaries of ecosystem services (NRC 2004).

Ecosystem services are potentially useful concepts for policy analysis because they can be used as performance measures for different management strategies. It is not necessary to quantify an entire ecosystem to weigh policy choices. Rather, management strategies can consider the connection of physical changes in the ecosystem to a set of changes in ecosystem services (NRC, 2004). Translating these resulting changes into a monetary value, as is commonly done in benefit-cost analysis, is another possible way of evaluating management alternatives, but not a necessary one.

2.5 A Systems Approach to Managing Puget Sound

A system-wide approach can assist resource managers within the Puget Sound ecosystem to forecast changes in ecosystem services across different scenarios (MA, 2004; especially chapter 4). This approach is useful for revealing possible tradeoffs in particular services. Consider the following instances from Puget Sound:

- Shoreline armoring enhances property values (a cultural ecosystem service) but can also interfere with beach sediment supply and result in losses of shoreline vegetation (supporting services) and declines in the species that depend on such vegetation, such as herring and other forage fish. This can result in declines in higher level predators that depend on such forage fish, such as salmon. Salmon declines can lead to reductions in commercial and recreational fishing (a provisioning service) and whale watching (a cultural service), since salmon are a significant portion of the diets of Orcas in Puget Sound. Thus in this example, the benefits of shoreline armoring for private and public property owners could result in losses to fishing and whale watching economies.
- Dams can produce power generation and water for irrigation (provisioning services) but can also harm salmon populations and interfere with sediment transportation (a supporting service). Disrupted sediment transport from rivers can starve beaches at river mouths, reducing opportunities for beach-combing (a cultural service) or shellfish aquaculture (a provisioning service), for example.
- Fish harvests (provisioning) may be unsustainable if their level is too high and can reduce marine nutrient transport (a supporting service) to freshwater habitats. Similarly, timber harvest (another provisioning service) can deplete nutrient availability in upland terrestrial and freshwater habitats. Reductions in nutrient availability in upland habitats can result in reduced tree growth, and declines in large mammal, bird and fish populations. These changes will ultimately affect the provisioning services of fishing and forestry, as well as cultural services such as eco-tourism.

As illustrated by these examples, enjoying the ecosystem services that Puget Sound is capable of providing involves a delicate balancing act. Ecosystem services are based on what humans find valuable about the natural world. Too much use of the ecosystem, or an emphasis on one type of service at the expense of another, can severely reduce the capacity of the ecosystem to support a broad range of services. For this reason, there will often be tradeoffs. The complex linkages within ecosystem processes often cause these tradeoffs to be invisible unless these connections are made fully transparent. As shown in the first example provided above, it may be difficult to trace the relationship of shoreline armoring to the whale watching industry. The major challenge of ecosystem management is to find ways to assess these tradeoffs and move the integration of the human and natural systems towards a better balance.

An essential element of an ecosystem approach is to understand how habitat-forming processes (such as currents and tides, nutrient cycling, and sediment transport) affect habitat structure and species interactions. In addition, a strong characterization of the interactions between species, and between species and habitats is a critical component of managing the ecosystem effectively. These linkages are necessary in identifying how human behavior and management actions can work together to achieve ecosystem goals, and where conflicts and tradeoffs are likely to occur. The mechanisms by which the Puget Sound ecosystem produces goods and services are not entirely understood, and the method used to assign values to those goods and services is in its infancy. However, as described in Section 3, considerable information exists about the components of the Puget Sound ecosystem that can be used to inform early actions for achieving Puget Sound goals.

Section 3: The Puget Sound Ecosystem: Changing Ecological and Human Components

The natural wealth produced by the Puget Sound ecosystem has attracted and sustained human inhabitants for thousands of years. It is the structure and function of the ecosystem that keeps those goods and services coming in the form of fish, timber, clean water and other benefits. Puget Sound retains a geological legacy from active glaciers and volcanoes which formed mountains, river valleys, marine basins and islands. The variable upland and underwater topography of the Sound is overlaid by complex physical and chemical processes that have given rise to diverse habitat types and species. Increasingly, however, the actions of humans have also become drivers of ecosystem change.

Although the intricate and interdependent connections within Puget Sound are not entirely understood, Section 3 briefly describes the key components of the Puget Sound ecosystem including:

- **Natural physical and chemical processes** that play a role in the structure and functioning of the ecosystem, including climate, marine water circulation, element cycling, and connections between freshwater or terrestrial systems and the marine system.
- How these processes form and sustain **habitat structure and the distribution of habitat types.**
- The effect of processes and habitat quality, quantity and distribution on the **community of species and the food webs** of the Puget Sound ecosystem.
- The changing role over time of **humans in the ecosystem** as users of its goods and services, influences on its structure, and how our actions have resulted in large-scale ecosystem change.

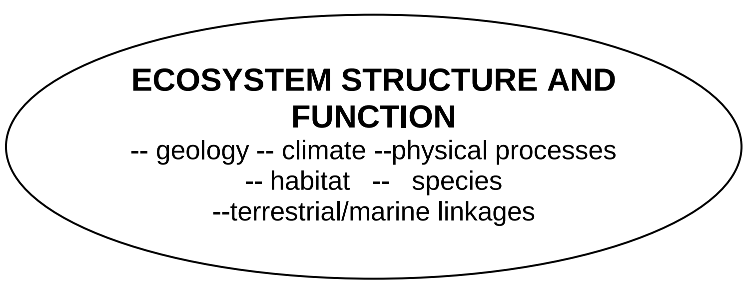

Figure 3-1: Map of the Puget Sound Region and Major Sub-basins

[This is a placeholder. Will use a map with the major sub-basins delineated.]

3.1 Geographic Overview of the Greater Puget Sound Region

The greater Puget Sound region[1] includes the lands from the crests of the Cascade and Olympic mountains to the shores of marine waters extending from the mouth of the Strait of Juan de Fuca east including the San Juan Islands and south to Olympia (Figure 3-1). The marine waters comprise a large, complex estuary that covers an area of approximately 2,330 km^2, including 3,700 km of shoreline, and is fed by thousands of streams and rivers that drain a total land area of about 35,500 km^2. On average, Puget Sound south of Admiralty Inlet has a depth of 62.5m, but ranges to nearly 300m at its deepest. This depth is the result of relatively recent geologic events, as 10,000 years ago mile-thick glaciers pushed southward into the basin, carving deep fjords and depositing sediments hundreds of meters thick.

The Puget Sound region has a number of unique attributes that make the ecosystem sensitive to change and that should influence regional approaches to ecosystem protection and restoration. The Cascade and Olympic mountain ranges create highly variable local climate patterns and a diversity of habitat types and species, from alpine meadows to the depths of Puget Sound. Projected changes in global climate are rapidly translated into local climate impacts in the Puget Sound region because of its variable topography. Flows in both glacier-fed rivers and streams in lowland areas are very sensitive to changes in climate attributes such as precipitation and air temperature.

[1] Puget Sound as used throughout this document refers to the greater Puget Sound region including the Strait of Juan de Fuca and the San Juan Islands. This definition has been selected to correspond with the Governor's Puget Sound Initiative to develop management recommendations throughout a broadly inclusive area.

The striking variability in regional topography continues underwater in the form of steep bathymetry, resulting in very deep water close to shore. The steeply sloping sides of Puget Sound allow for only a narrow fringe of vegetated habitat near the shoreline where light can penetrate the water. Puget Sound is unique among estuaries in this country due to its fjord-like shape and form, and the underwater structure of the basin that restricts the circulation of water, sediment, many living organisms and contaminants.

Based primarily upon geomorphology, extent of freshwater influence, and oceanographic conditions, Puget Sound can be sub-divided into five major basins: North Puget Sound, the Main Basin, Whidbey Basin, South Puget Sound and Hood Canal.[2] Each of these basins differs somewhat in features such as temperature regimes, water residence and circulation, biological conditions, depth profiles and contours, processes, species, and habitats (table ____).

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[2] Several methods have been used to delineate sub-basins within Puget Sound for different programs, e.g. ambient monitoring and salmon recovery. This division into 5 sub-basins is used here to highlight some of the key bathymetric, circulation and habitat differences in portions of the Puget Sound ecosystem.

Table ___: Key physical attributes of major Puget Sound basins:

Geographic Basin	Major Attributes
Northern Puget Sound: Geographic features include the Strait of Juan de Fuca (SJF), Admiralty Inlet, the San Juan Islands, and the southern part of the Georgia Strait.	o The western SJF is strongly influenced by ocean currents while the eastern end is influenced by intense tidal action in numerous small passages. o Surface flow in the SJF is primarily seaward, with the exception of easterly flow along the shoreline between Port Angeles and Dungeness Spit, landward flow in many embayments, and flows of surface water southward toward the Main Basin near Admiralty Inlet. o Waters of the SJF are well mixed vertically, and variations in temperature and salinity are low. o Freshwater runoff makes up about 7% of the volume in the SJF and is primarily derived from the Fraser River. o This region contains approximately 93% of the rocky reef habitat in Puget Sound (approx 200km^2) o About 45%of the shoreline of this region consists of kelp habitat (compared to 11% in other Puget Sound basins). o Approximately 71% of the area draining into Northern Puget Sound is forested, 6% is urbanized and 15% is used for agriculture; the basin is the most heavily used for agriculture of the basins in Puget Sound. o WDNR estimates that 21% of the shoreline in this basin has been modified by human activities.
Main Basin: Geographic features include Sinclair and Dyes inlet and Colvos and Dalco passages on the west side, and Elliott and Commencement bays.	o Major bathymetric features include the sills at the north end of Admiralty Inlet and the Tacoma Narrows. o 30% of the freshwater flow into the Main Basin is derived from the Skagit River. o The Main Basin is generally stratified in the summer due to river discharge and solar heating, and mixed in the winter due to cooling and wind. o Oceanic waters from the SJF flow over the northern sill at Admiralty Inlet. o In the southern section, currents generally flow northward along Colvos Passage on the west side of Vashon Island, and southward on the east side through the East Passage. o The sill at Tacoma Narrows causes an upwelling process that reduces the seawater/freshwater stratification. o Major circulation patterns in this basin are greatly influenced by decadal climate regimes. o The Main Basin has a relatively small amount of intertidal vegetation, predominated by green algae and eelgrass. Most eelgrass is located on the western shores of Whidbey Island and the eastern shores of the Kitsap Peninsula. o Areas bordering the Main Basin include the major urban and industrial areas of Puget Sound, and 80% of the waste discharged from point sources into Puget Sound comes from this region. o Approximately 70% of this drainage is forested, 23% is urbanized and 4% is used for agriculture. o WDNR estimates that 52% of the shoreline in this area has been modified by human activities.

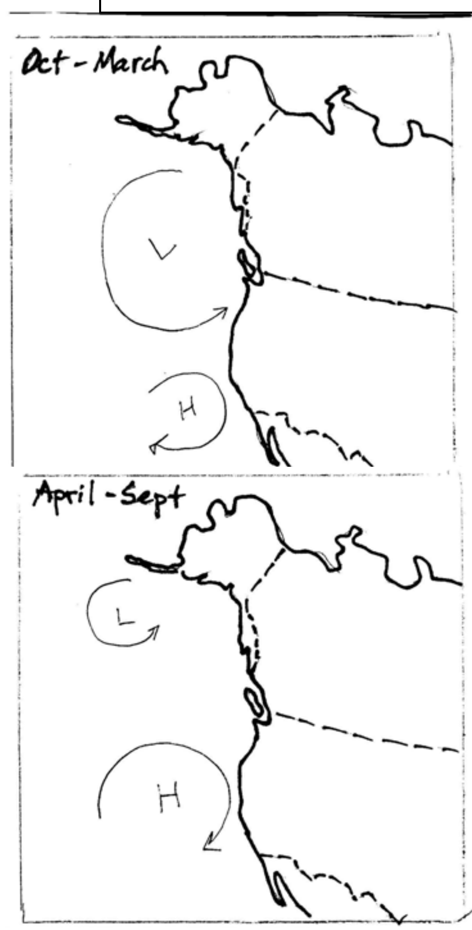
Whidbey Basin: Includes the marine waters east of Whidbey Island, and the delta areas for the 2 largest river systems in Puget Sound – the Skagit, and Snohomish.	o Waters in this basin are generally stratified, with warmer surface waters in the summer. o Salinity in the northern portion of the basin is generally lower than the Main Basin due to the major rivers. o Predominant forms of intertidal vegetation include green algae, eelgrass and salt marsh. Eelgrass beds are most abundant in Skagit Bay and the northern portion of Port Susan. o Approximately 85% of the drainage area of this basin is forested, 3% is urbanized and 4% is in agricultural production. o Approximately 60% of the nutrients (as inorganic nitrogen) entering Puget Sound enter through the Whidbey Basin by way of the major river systems. o WDNR estimates that 36% of the shoreline in this basin has been modified by human activities.
Southern Puget Sound: Includes all waterways south of the Tacoma Narrows. This basin is characterized by numerous islands and shallow inlets with extensive shoreline areas. The largest river entering this basin is the Nisqually.	o Currents in this basin are strongly influenced by tides due largely to the shallowness of this area. o In general, surface waters flow north and deeper waters flow south. o Major channels in the southern basin are moderately stratified because no major river systems flow into the basin. o Temperatures in the inlets are elevated in the summer. o This basin has the least amount of intertidal vegetation; salt marsh and green algae are the most common types. o Approximately 85% of this drainage is forested, 4% is urbanized and 7% is in agriculture. o Important sources of waste include sewage treatment facilities from urban centers and a paper mill in Steilacoom. Non-point sources from this basin contribute 5% of the nutrients (as inorganic nitrogen) entering Puget Sound. o WDNR estimates that 34% of the shoreline in this basin has been modified by human activities.
Hood Canal: Major geographic features are the Entrance, Dabob Bay, the central region and the Great Bend. Dabob Bay and the central region are the deepest portions, while other areas are relatively shallow.	o Like many of the other basins in Puget Sound, Hood Canal is partially isolated by a sill at its entrance that limits the transport of deep marine waters. o Aside from tidal currents, currents in hood Canal are slow. The strongest currents tend to occur near the entrance and involve a northerly flow of surface waters. o Portions of the Canal are stratified with marked differences in temperature and dissolved oxygen between the entrance and the Great Bend. o Saltmarsh and eelgrass are the most abundant intertidal plants; eelgrass is found throughout the Canal, especially in the Great Bend and Dabob Bay. o Hood Canal is one of the least developed areas in Puget Sound with 90% of the drainage forested, 2% urbanized and 1% in agriculture. However, the shoreline has been widely developed with seasonal and year-round residences. o WDNR estimates that 33% of the shoreline in this region has been modified by human activities.

3.2 Climate and Ocean Processes

The climate of Puget Sound is a product of the interaction between large-scale wind and weather patterns and the complex topography of the region. Seasonal changes in the movement of moisture-laden air which collide with the sudden barrier of the Olympic and Cascade Mountains bring Puget Sound the record-breaking precipitation for which it is so famous. These circulation and topographic differences also lead to remarkable climate differences within Puget Sound itself, influencing the species and habitats that dwell in the Sound.

3.2.1 The Aleutian Low

Figure ____: Seasonal changes in weather patterns in the Pacific Northwest region. placeholder



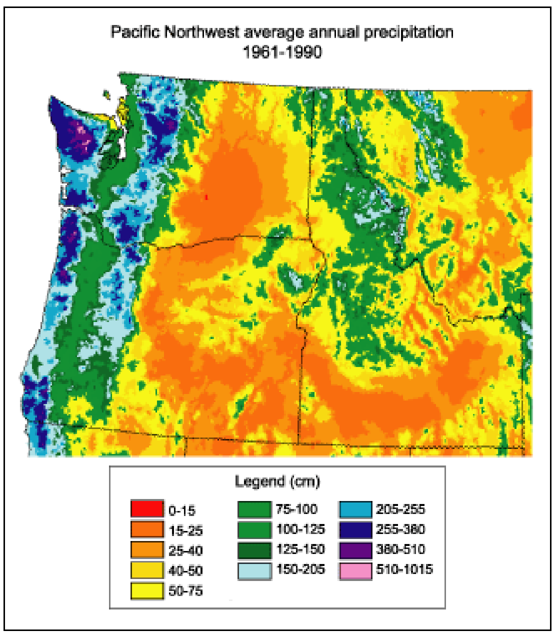
low

Beginning about mid-October a semi-permanent low-pressure cell, commonly called the *Aleutian Low*, intensifies and migrates southeastward over the Aleutian Islands and Gulf of Alaska. Surface winds blow in a counterclockwise circulation around the Aleutian Low. Further south, winds blow in a clockwise circulation around a semi-permanent center of high pressure typically centered offshore of southern California. Together, these high and pressure cells typically bring moist, mild, onshore flow into the PNW from October through early spring (Figure ___). As the moisture-laden air encounters the Olympic or Cascade Mountains, it rises and cools, and the cooling causes water vapor to condense into liquid cloud and rain drops. Because of the seasonal shifts in large scale wind patterns, the PNW's wet-season typically begins in October, peaks in mid-winter, and ends in the spring; about 75% of the region's annual precipitation falls in the period October-March. During late spring, the Aleutian Low retreats to the northwest and becomes less intense, while the high pressure cell to the south expands northward and intensifies. The result is a strong reduction, from late spring through summer, of landfalling storms for the Pacific Northwest.

3.2.2 Precipitation Patterns and Localized Variability

The west (windward) slopes of the Cascade and Olympic mountains receive enormous quantities of rain and snow, exceeding 200 inches (5 meters) of water equivalent per year at some locations on the Olympic Peninsula. At Paradise Ranger station on Mount Rainier, the average spring sees an end of season snow depth of ~170" (4.1 meters). The Cascades are often among the snowiest places on Earth: in 1956 the snow at Paradise piled to a depth of nearly 30 feet (9.1 meters) during a year in which that location's annual snowfall was nearly 94 feet (28.5 meters); the Mount Baker Ski Area, located in the north Cascades near the U.S./Canada border, set a new *world record* for the highest annual snowfall ever recorded (October-September) in 1998-99 with a total of 96 feet (29 meters; Bell et al. 2000).

Insert precip map of western WA: This is a placeholder from the CIG website.



Although the west side of the Cascades is generally a very wet region, it contains several areas that receive significantly less precipitation than the west-side average. Washington's Puget Lowlands, the northeast extreme of the Olympic Peninsula, and the San Juan Island archipelago are relatively dry areas that lie in "rain shadows." Rain shadows in these areas are caused by Olympic Mountains located to the west and southwest that shields them from the direct impact of storms that follow the wet-season's prevailing storm track.

The Cascade Mountains also bear strongly on seasonal variations in the region's climate. West of the Cascades, the low-lying valleys have a maritime climate with typically abundant winter rains, infrequent snow, dry summers, and mild temperatures year-round (usually above freezing in winter, so that snow seldom remains for more than a few days). East of the Cascade crest, the region's climate is much more continental, with rainfall and cloudiness less common and sunshine and dry conditions more common, year-round. On a finer scale, gaps and low-elevation passes in specific locations provide connections between the east-west climate differences, affecting habitat-forming processes and the spatial distribution of the biota of the west slopes of the Cascade mountain range.

Box ___: Coastal Upwelling

An ecologically important consequence of the seasonal changes in PNW coastal winds is the relationship between wind patterns, currents and the input of nutrient-rich waters, a phenomenon known as "coastal upwelling." The switch from northward, winter wind patterns to more frequent southward winds in the summer months drives ocean surface currents offshore which are replaced by cool, nutrient-rich waters from greater depths. Upwelling is important for marine ecosystems because it helps to supply nutrients to the upper ocean where sunlight is generally abundant during the summer. Phytoplankton require a combination of sunlight and nutrients to produce food through photosynthesis, and high phytoplankton production helps fuel high productivity throughout the marine food web.

This will have an illustration.

3.2.3 The El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)

The year-to-year and decade-to-decade changes in the strength and location oaf the Aleutian Low has been a prominent feature of Pacific climate variation in the last century. Climate records indicate that one of the most prominent features of Pacific climate variations is expressed through year-to-year and decade-to-decade changes in the strength and location of the Aleutian Low pressure pattern. This is of special importance for Puget Sound because an intense Aleutian Low brings relatively warm and dry winters to the region, while a weak Aleutian Low favors a cooler and wetter winter. Variability in the Aleutian Low comes from a variety of sources, but two important influences on the Aleutian Low are the large scale variations in sea surface temperatures known as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

ENSO is a natural part of Earth's climate that spontaneously arises from interactions between tropical trade winds and ocean surface temperatures and currents near the equator in the Pacific. Warm extremes of the ENSO cycle, commonly called El Niño, favor an especially intense Aleutian Low, which is associated with the displacement of the storm track in the eastern North Pacific. As the displacement moves the track southerly towards California, the conditions favor a warm and mild Puget Sound winter. Cold extremes of the ENSO cycle, commonly called La Niña, favor the opposite. Individual ENSO events (either El Niño or La Niña) typically occur over the course of a single year, and over the past century one year in four (on average) has been an El Niño extreme, and one year in four has been a La Niña extreme.

The Pacific Decadal Oscillation plays out over a longer timescale, with a typical lifetime of 20 to 30 years for the extremes. Warm eras of the PDO prevailed from 1925-46 and from 1977-98, while cold eras prevailed from 1900-24 and 1947-76. Warm eras of the PDO are associated with a prevalence of intense Aleutian Low winters, while cold eras are associated with weak Aleutian Low winters.

Insert PDO graph. This is a placeholder from the CIG website.

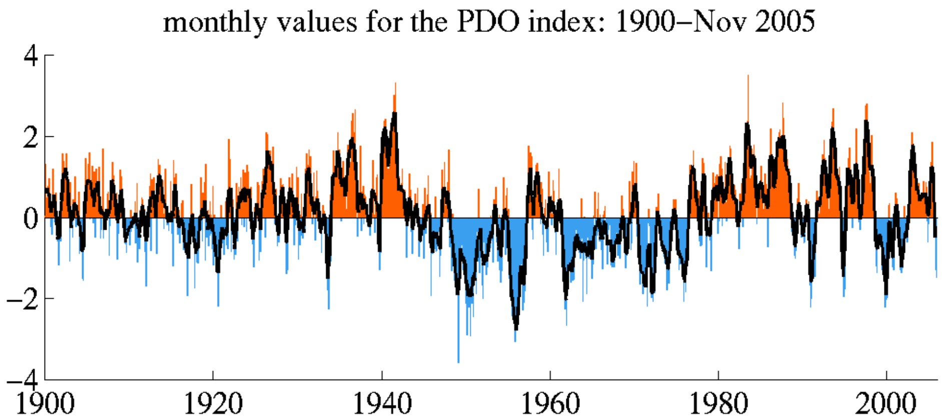
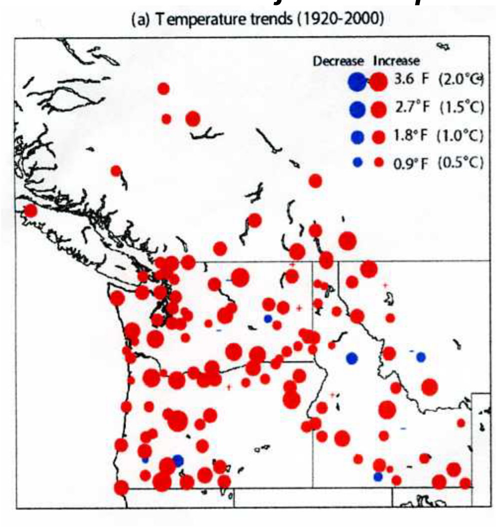


Figure 2 Monthly Values for the PDO Index, January 1900 to February 2003. Positive (red) index values indicate a warm phase PDO; negative (blue) index values indicate a cool phase PDO. While short-term flips in PDO phases do occur, evaluation of 20th century instrumental records has shown that PDO phases generally persist for 20-30 years, as indicated in this figure.

Because the PDO and ENSO have similar impacts on the character of the Aleutian Low, both La Nina and cool PDO periods are typically accompanied by cooler than average sea surface temperature, shallow thermocline (temperature layer), and high productivity. Warm periods (typical of warm PDO and (El Niño periods) are characterized by warmer sea surface temperatures, deeper thermocline and lower productivity. Biological changes throughout the ecosystem in the northeast Pacific Ocean are associated with different climate regimes—including changes in zooplankton, benthic algae, meso-crustaceans, rocky reef fishes and apex predators. The effects of regime shifts vary geographically--Pacific salmon from Alaska increased in abundance in response to the 1976 regime shift while populations from the Pacific Northwest declined.

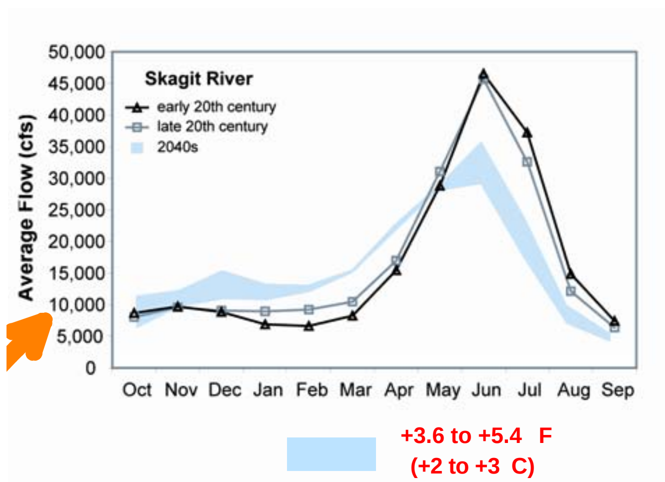
Potential changes in global climate patterns are likely to have important consequences to Puget Sound ecosystem processes. Changes in precipitation, temperature and the frequency of intense Aleutian Low systems will alter freshwater input, nutrient cycling and stratification with ramifications throughout the food web. The Climate Impacts Group at the University of Washington has published two important reports (Snover et al. 2005; Mote et al. 2005) that document a number of potential impacts that climate change may have on the Puget Sound ecosystem (Box ___). More information on climate change is contained in part 4.

Box ____:
Observed and Projected Impacts of Climate Change in the Pacific Northwest



Based on extensive review of climate records, the University of Washington Climate Impacts Group concluded that there is compelling evidence for climate change in the Puget Sound Region. Evaluation of temperature records, for instance, shows that nearly every climate record in the Pacific Northwest shows evidence of substantial warming. Climate models predict an average rate of warming of 0.34°C per decade through 2040.

Trends in precipitation are less clear, but most monitoring stations show increases. However, as rising temperatures cause mountain snowpack to diminish, PNW rivers will see reduced summer flow, increased winter flow, and earlier peak flow. Monitoring by the CIG shows that these trends have already been observed, with more water entering the Sound earlier than historically.



The amount of water currently entering Puget Sound between June-September has declined by 18% as compared to the historical record. Additionally, most of the glaciers in the region have been retreated for 50-150 years, affecting flow rates in some systems.

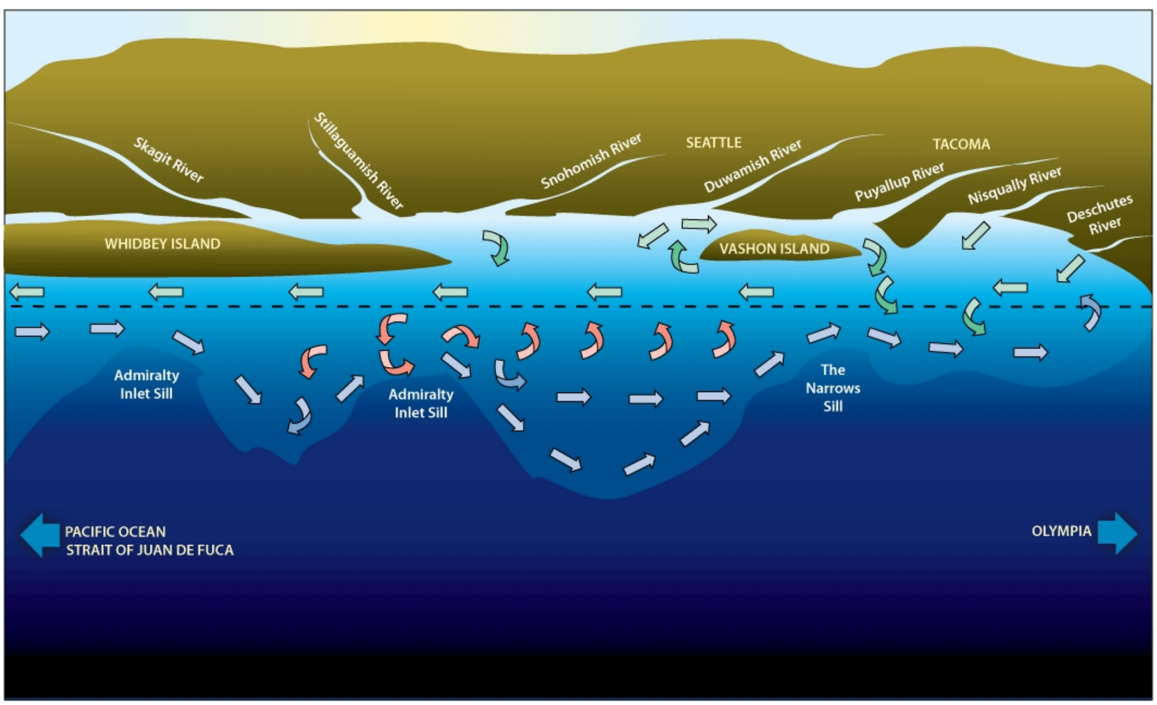
Land in some regions of south Puget Sound is sinking more than 2 mm per year, while portions of north Puget Sound appear to be stable. Overall sea level increases in South Puget Sound could be up to 1 meter in the next 100 years. Additionally, some climate models predict shifts in winds that could increase sea level rise by an additional 20 cm in some regions of the Sound.

3.3 Physical Processes within Puget Sound

3.3.1 Circulation in Puget Sound

Puget Sound circulation is driven by freshwater flows into Puget Sound, wind strength and direction, tidal currents, and bottom saltwater intrusions from the Strait of Juan de Fuca. Estuarine circulation is typically two-layered, caused by the surface outflow of fresh water from river runoff, and deep inflow of salt water from the ocean. Deep, dense salt water enters Puget Sound through Admiralty Inlet, and part flows south into the Main Basin and part flows north up into Whidbey Basin. The resulting landward-flowing water replaces the bottom water of Puget Sound and keeps it from becoming stagnant, and the out flowing surface water flushes Puget Sound (Figure ____). The rate at which water flows out of Puget Sound is dictated in part by upwelled deeper salt water and the amount of freshwater flows entering the Sound through the major river systems. Because of shallow sills at Admiralty Inlet, the Tacoma Narrows, and the mouth of Hood Canal, some fraction of the water and its dissolved and suspended constituents do not leave the area immediately, but make additional trips through sub-basins of Puget Sound.

Figure ____: Circulation patterns and major sills in Puget Sound (in progress).



Within the main basin of Puget Sound, an exception to the typical two-layered flow pattern occurs along Vashon Island, where the outflow from the Narrows is a driving force. Puget Sound is actually a collection of smaller estuaries with various flow patterns influenced by freshwater input and tidal mixing.

Superimposed over the two-layered circulation pattern are the tidal currents that dominate the circulation observed in Puget Sound. The movement of water due to tides is about 5-10 times larger than the estuarine circulation seen throughout the Sound. As the tidal currents flow past points of land, the water forms eddies in the lee of the points. These tidal eddies provide a transport mechanism for offshore water to reach the shoreline, bringing nutrients and plankton to nearshore communities. Tidal currents in the main basin of Puget Sound, a region with depths of 200 m or more, typically are less than 0.25 meter per second. In contrast, tidal currents in Admiralty Inlet and in The Narrows, regions with depths of 40-80 m, can be as large as 2.2 and 3.3 m/s, respectively (NOAA, 1984).

The large tidal exchanges and distinctive bathymetry and shallow sills within Puget Sound mean that the flushing rate of waters and the sediments and dissolved constituents they carry are restricted and slowed, and the sills prevent sediment, many organisms and contaminants from readily leaving Puget Sound. Water movement also plays an important role in shaping the location and quality of shoreline, nearshore, and deep water habitats of Puget Sound. An understanding of general circulation conditions is essential to the assessment of element cycling throughout the ecosystem, as well as site specific conditions for locating facilities such as sewage treatment plants.

3.3.2 Element Cycling and Stratification

Nutrient concentrations in the upper layers of the ocean tend to be lower than in the deeper waters due to the utilization by phytoplankton in the euphotic (i.e., sunlight-rich) zone. Replenishment of nutrients in the upper layers can be accomplished through coastal upwelling, vertical diffusion from deeper waters, and contributions from land through rivers,streams, treatment plants, stormwater, and runoff. Certain nutrients, including nitrogen and phosphorus, are necessary for phytoplankton growth.

The process of vertical mixing between surface and underlying waters is a major driver of nutrient and phytoplankton dynamics, which in turn affect dissolved oxygen (DO) levels. Stratification refers to the horizontal layering of water masses due to density differences.

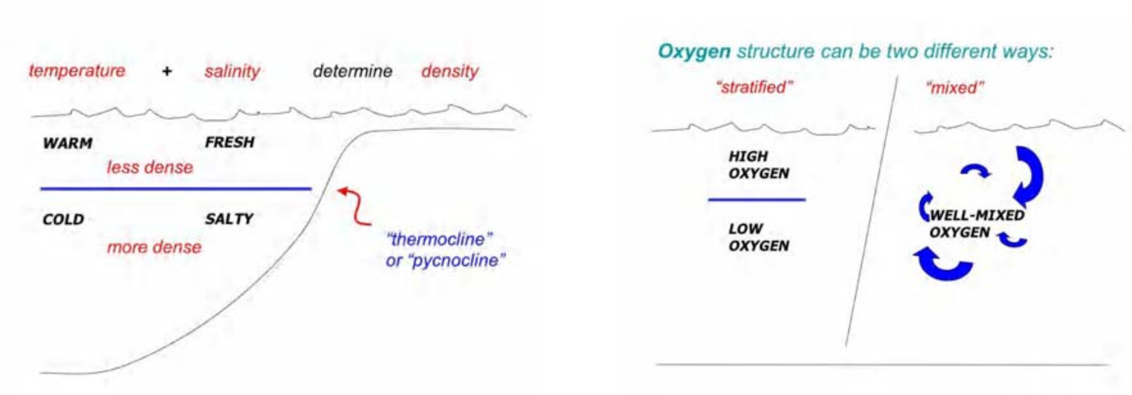


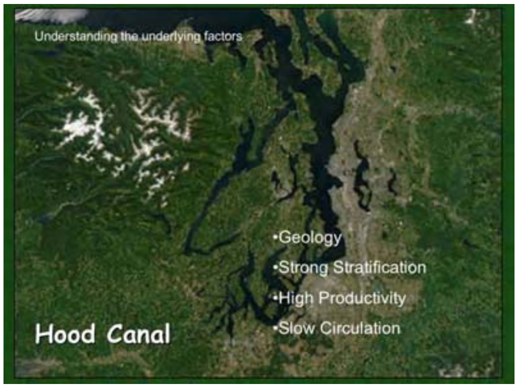
Figure ___: Stratification and oxygen structure in estuarine waters. (This is a placeholder figure taken from the Hood Canal Dissolved Oxygen Program website www.hoodcanal.washington.edu.

The development of stratification within the water column is significant because of the physical barrier it presents with respect to vertical water movement. For example, turbulent eddies, driven by winds and tides, cause vertical mixing of phytoplankton, dissolved oxygen, and nutrients. If, however, the water is stratified, then the ability of turbulent eddies to accomplish vertical mixing will be greatly decreased. This is particularly true at the pycnocline, which is often observed in the top several meters of the water column. (Figure __). Thus stratification effectively isolates the surface water from the deep water.

When stratification is intense, two environmental conditions can result--surface waters can become depleted of nutrients (dissolved nitrogen and phosphorus), and bottom waters can become depleted of oxygen. When external supplies of nutrients are increased in a system that exhibits low circulation and stratification, the condition can result in dense algal blooms (Box ___ on Harmful Algal Blooms --section 3.6) and, after the algae sink and decay, a correspondingly large deficit of dissolved oxygen in bottom waters (Box __Hood Canal).

Low precipitation can lead to reduced river flows that can markedly affect water properties. For instance, reduction of freshwater inflow in the 2000-2001 drought reduced the density difference between surface and bottom waters in Puget Sound. Although weakened stratification allows localized vertical mixing, it can reduce the flushing pattern of Puget Sound as a whole. If the pattern of estuarine circulation (figure ___) is weak, the movement of organisms and nutrients in the top layer towards the ocean will be reduced. Altering exchange rates between the Sound and the coastal ocean has implications for the dispersal of numerous small species of open-water invertebrates and fish larvae as well as water quality within the Sound.

Box ___: Dissolved Oxygen and Water Quality in Hood Canal and South Puget Sound



Hood Canal:

Low dissolved oxygen (DO) concentration in Hood Canal is not a new phenomenon, but considerable evidence suggests that this problem has increased in severity, persistence, and spatial extent (Newton, et al., 2002). The most severe low DO conditions occur in the southern end of the canal, the point furthest from water exchange with the rest of Puget Sound. Comparing oxygen data from 1930-1960s with data from 1990-2000s shows that in recent years the area of low dissolved oxygen is getting larger, spreading northwards, and that the periods of hypoxia last longer through the year.

Although records of fish kills in Hood Canal date as far back as the 1920's, repetitive fish kills during 2002, 2003, and 2004 indicate that the increasing hypoxia may be having biological consequences. In 2003 the Washington Department of Fish and Wildlife closed Hood Canal to commercial and recreational fishing for all finfish except salmon and trout and for octopus and squid. This was the first time in Washington State's history that a fishery was closed due to a water quality issue such as low dissolved oxygen.

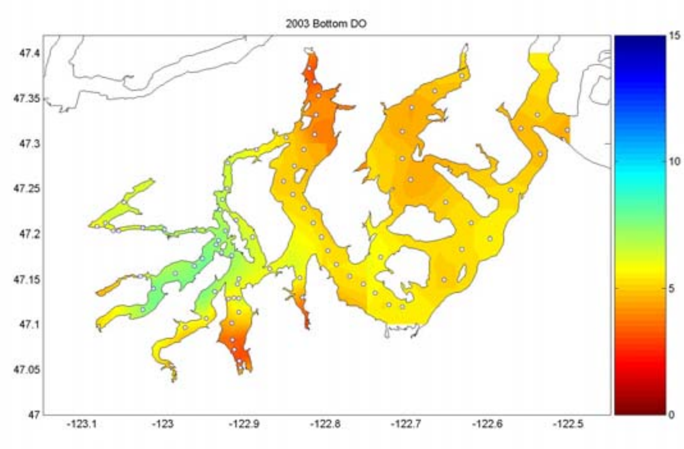
A number of physical, chemical, and biological factors are thought to contribute to the low dissolved oxygen conditions in Hood Canal. These include: the circulation and flushing of the canal, which is affected by ocean and river waters; the degree of seawater stratification, which controls vertical mixing and is affected by river, ocean, and weather conditions; the productivity of algae, which is affected by sunlight; and nutrient (nitrogen) and carbon availability, which can come from both natural and human sources. Like classic fjords, Hood Canal is prone to hypoxia because deep-water exchange with Puget Sound is limited by a shallow sill at the outlet of the canal and thus circulation in Hood Canal is slow relative to other Puget Sound basins (Warner et al., 2001). Anthropogenic sources of nitrogen, such as septic system and hatchery discharges, fertilizer use, and salmon carcass disposal, may thus stimulate phytoplankton growth, increase microbial decomposition and subsequently decrease dissolved oxygen levels. Although overall human population density in the Hood Canal basin is generally low, shoreline development is intensive in a number of regions of the canal and may influence oxygen conditions.

The Hood Canal Dissolved Oxygen Program and its Integrated Assessment and Modeling study (HCDOP-IAM) arose out of the need to quantify what is driving the increasing hypoxia, to address whether human activities (and which ones) are major causes, and to evaluate the efficacy of potential corrective or mitigative actions. These programs are described at www.hoodcanal.washington.edu.

South Puget Sound

Residential development in South Puget Sound has risen dramatically over the past two decades, raising concern that its waters could be adversely affected by the increased nutrient and pollutant loading that typically accompanies a growing population. The South Sound is particularly susceptible to water quality problems because its many blind inlets and distance from incoming oceanic waters contribute to high water residence times and slow the rate at which pollutants and nutrients are flushed into greater Puget Sound and ultimately the Pacific Ocean. At present, several South Sound locations have already been identified as impaired under federal Clean Water Act criteria for dissolved oxygen, fecal coliform bacteria, and other variables. The Washington State Department of Ecology completed phase I of the *South Puget Sound Water Quality Study* in 2002 to measure existing water quality and assess the potential for future water quality problems.

The study found that phytoplankton productivity in parts of the South Sound increased significantly when nutrients were added and that low dissolved oxygen occurred in several inlets, with Case, Carr, and Budd inlets appearing to be the most susceptible. The Phase 1 report is available at http://www.ecy.wa.gov/pubs/0203021.pdf .



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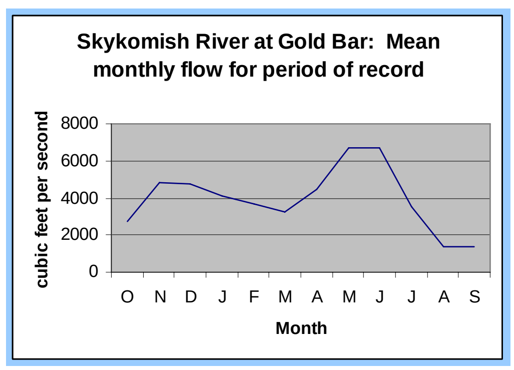
3.4 Connections between Terrestrial, Freshwater and Marine Habitats.

The terrestrial and freshwater habitats in the Puget Sound region span high elevation glaciers and alpine meadows. Mid-elevation forests of Douglas Fir, Western Hemlock, Red Alder, and big-leaf Maple drop to lower elevation areas that historically supported stands of Spruce, Cedar, and Pacific Madrone (Kruckeberg 1991). The elevation of the Cascade and Olympic peaks--exceeding 4,000 m, drops dramatically to sea level on the shores of Puget Sound in a short linear distance. Powerful rivers spill from glaciers over this steep terrain and pass through the diverse forest communities. In the process, the rivers create dynamic riparian zones, and may change channel locations several times throughout a decade as they migrate throughout their floodplain.

Streams and rivers in the watersheds of Puget Sound transport water, wood, sediment, organic matter and nutrients downstream where they influence freshwater and estuarine ecosystems. The delivery of these building blocks of habitat create a variety of habitat types within the river system and near the river mouth, including low elevation forests, freshwater and saltwater marshes, and numerous shoreline and beach habitats, all utilized by Puget Sound's fish and wildlife. Circulation of water, nutrients and sediment continues along the shoreline interface and throughout the estuary via tidal action, gravitational forces, and freshwater inflows. Substantial quantities of nutrients are returned to the upland environment through the movement of thousands of animals, notably the returning runs of adult salmon.

3.4.1 Freshwater Discharge in Puget Sound



Fresh water flows are important determinants of aquatic food web function, estuarine and nearshore habitat structure, and circulation in the marine waters of Puget Sound. Coastal areas within Puget Sound generally are characterized by high levels of rainfall and river discharge in the winter, while inland mountains are characterized by heavy snowfall in the winter and high snowmelt in late spring and early summer. This local weather pattern creates two major periods of freshwater runoff into Puget Sound with maxima in December and June.

The major sources of freshwater from Puget Sound river systems are from the Skagit and Snohomish watersheds in the Whidbey Basin; however, the annual amount of freshwater entering Puget Sound is only 10 to 20% of the amount entering the Strait of Georgia, primarily through the Fraser River (NOAA-NWFSC TM44). (Fig. 3.#--map with arrows showing flow levels).

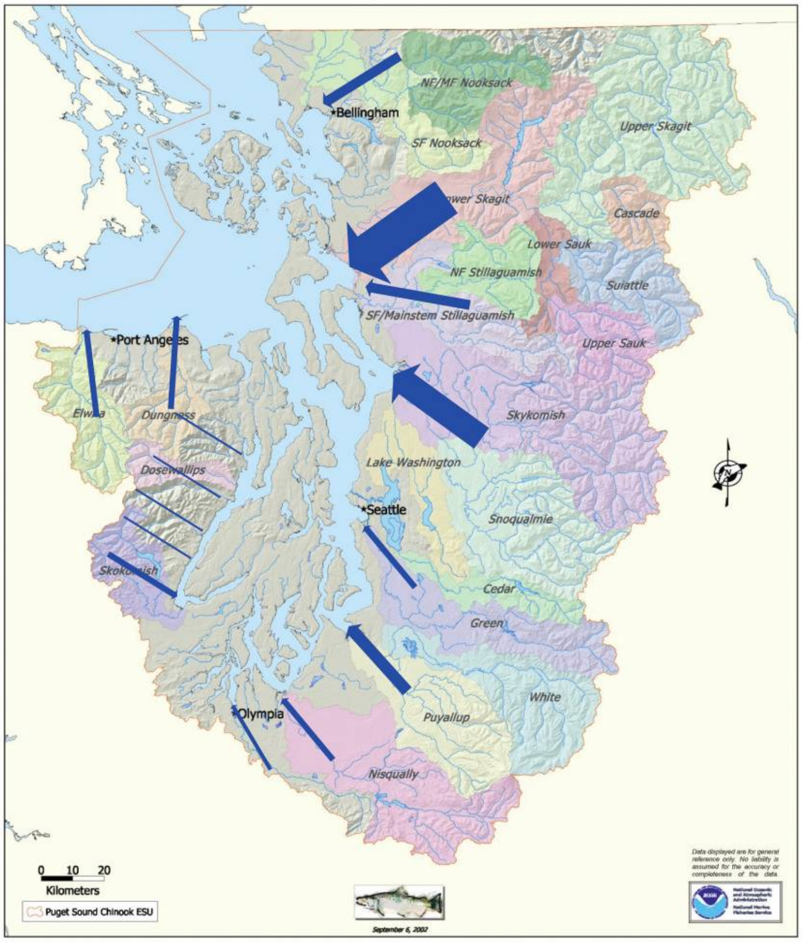


Figure 3.__. Annual freshwater inflows from Puget Sound Rivers are a major driver of marine circulation patterns FRASER RIVER TO BE ADDED (this is a placeholder figure)

3.4.2 Shoreline Formation and Sediment Transport Processes

Puget Sound has over 4,000 km (2,500 miles) of shorelines, ranging from rocky sea cliffs to coastal bluffs and river deltas. The exchange of water, sediment and nutrients between the land and sea is fundamental to the formation of an array of critical habitat types. Sediments ranging from gravel to fine silts and sands are eroded from river edges and transported downstream and into estuarine and nearshore habitats. These river sediments provide important gravels for salmon spawning and rearing in the freshwater system along the way. Further downstream, sediment is deposited at the river mouth forming extensive deltas with freshwater and saltwater marsh habitats for a multitude of fish, bird and supporting species. River sediment is an important contributor to the beaches along Puget Sound, but the erosion of bluffs along marine shorelines is also essential to the formation of beaches, sand spits, berms and other features (Figure ____). More far-reaching impacts of river-borne sediments also affect the Puget Sound marine environment. For example, suspended sediments carried in the Fraser River plume attenuate the light in the upper water column, thereby causing declines in primary productivity.

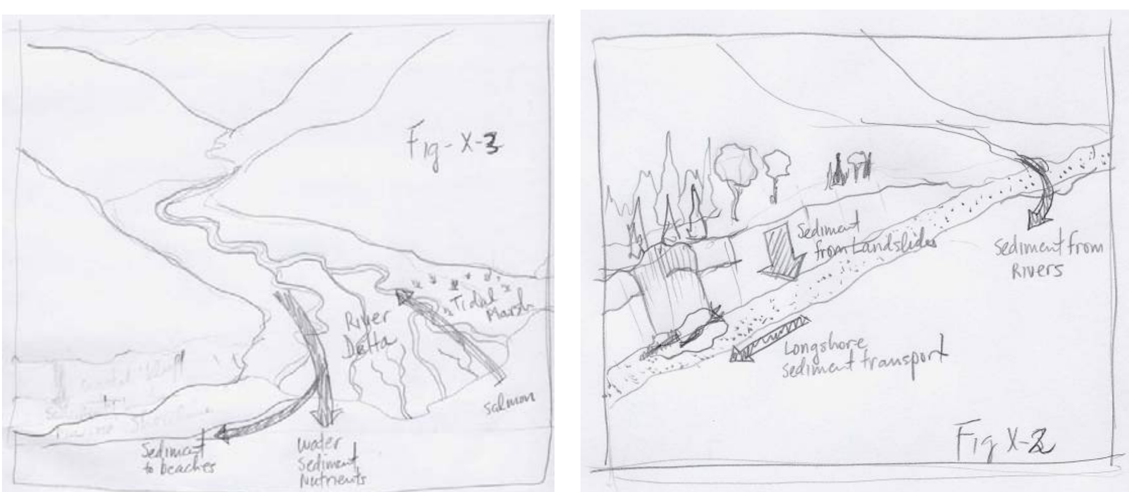


Figure ___: Sediment delivery and transport processes along Puget Sound beaches. (placeholder figure)

Terrestrial-aquatic exchanges generally occur at two distinct interfaces between freshwater and saltwater environments: 1) marine shorelines, and 2) river mouth estuaries.

<u>3.4.2.1 Marine Shorelines</u>

Marine shorelines in Puget Sound perform unique and critical ecosystem functions, providing the substrate for eelgrass and kelp, and supporting shellfish production, foraging by marine birds, rearing and migration for juvenile salmon and other services.

These shorelines consist mainly of coastal bluffs and sea cliffs. Sea cliffs are rocky cliffs with low erosion rates, often dropping steeply into deep water, and are more prevalent in northern Puget Sound, particularly the San Juan Islands. Most of Puget Sound's shorelines are coastal bluffs, which are composed of erodable gravel, sand, and clay deposited by glaciers over 15,000 years ago (Downing, 1983; Shipman, 2004).

Beach habitats along coastal bluffs are commonly delineated into "drift cells", which consist of zones of beach sediment transport separated by headlands, embayments or other landscape features. The volume of material added to beaches from bluff erosion is closely related to wave energy, as the sediment within a drift cell is moved along the beach by waves breaking along the shoreline. Hundreds of drift cells and net drift directions have been mapped for most of the Puget Sound shoreline (Department of Ecology, 1978; http://www.ecy.wa.gov/programs/sea/SMA/atlas_home.html; Schwartz et al., 1989; Schwartz et al., 1991). [will include a drift cell diagram]

Extensive development of coastal bluffs along the Sound has led to the widespread use of engineered structures designed to protect upland properties, railroads, and roads. Shoreline armoring can interrupt sediment transport processes, leading to burial or starvation of beaches in specific locations, increased wave energy or scour, and changes to habitat types such as eelgrass meadows, mud flats and salt marsh. These modifications have increased dramatically since the 1970s with substantial deleterious effect on the ecosystem health of the Sound (Thom et al. 1994).

Figure . Bluff failures contribute sediment to beaches (photo by Guy Gelfenbaum)

Figure . Railroad grade along shoreline from Seattle to Everett (photo by Guy Gelfenbaum)

3.4.2.2 River Deltas

Sediment is not the only factor affecting habitat formation along the terrestrial-aquatic interface. While the importance of large woody debris is well known for habitat formation within rivers and streams, the delivery of wood to deltas and shorelines is also necessary to ameliorate shore erosion and enhance nearshore habitats. This is especially the case in river deltas, where the wood can break up salt marsh and form patches of habitat for terrestrial species.

Historically, delta forests often consisted of sparse spruce, pine and alder groves but served as important habitats for many Puget Sound species such as raptors and beavers. The beaver modified and constructed expansive freshwater wetlands, used in turn by other species including juvenile salmon. Saltwater and freshwater marshes, and sand and mud flats on deltas, were historically dominant parts of the Puget Sound landscape, providing critical habitat and transitional zones for young salmon and many other species of birds, fish and mammals.

Physical destruction of habitat resulting from human development activities along river deltas has been severe in several major river systems in Puget Sound. Extensive marsh and nearshore habitats were eliminated by levees that separated rivers from their floodplain and delta, eliminating thousands of acres of habitat. Increasing urbanization and industrialization of many river deltas, including those of the Duwamish and Puyallup, have been so altered that there virtually remains no indication of their historical extensive saltmarsh habitat (Figure ___ Duwamish). These physical changes have led to dramatic habitat loss of salmon and other species that reside in or transit delta habitats.

Figure___: Duwamish River Delta (Shared Strategy, 2005)

Damming of rivers has locally reduced the flow of sediments to key nearshore environments, most notably at the mouth of the Elwha River [box]. Such reductions have resulted in significant beach erosion, costly shoreline protection measures, and loss of nearshore habitats. Dams have further restricted the river habitat accessible to salmon, reducing habitat capacity for salmon and eliminating the return of marine nutrients from portions of river food webs.

Box __-. Restoring Ecosystem Processes in the Elwha River

The Elwha River is one of ten major rivers on Washington State's Olympic Peninsula, and has 83% of its watershed located within Olympic National Park. Over 90 years ago, two dams were constructed 4.9 and 13 miles from the river mouth. Due to a lack of fish passage technology, the dams effectively blocked 10 runs of anadromous fish from returning to over 70 miles of spawning habitat in the upper Elwha River. Prior to dam construction, these fish numbered in the hundreds of thousands, making the Elwha River one of the most productive salmon rivers in the Pacific Northwest (Wunderlich et al. 1994).

The Elwha River drains part of the high Olympic Mountains and delivers sediment to the Strait of Juan de Fuca. Two large dams that have been in place for over 90 years are slated for removal in 2009.

The physical and ecological effects of the Elwha River dams were large and cumulative, with complex impacts to food web composition, habitat structure, and sediment transport that are only partially understood. Major changes to habitat-forming processes in the lower river, estuary and nearshore resulted from the blockage of large woody debris and sediment from the upper river. In addition to the obvious losses to fish populations, the upper river was depleted of marine-derived nutrients once provided by salmon carcasses. At least 22 species of birds and mammals were deprived of this important nutrient source, creating cascading effects in the riparian and upland areas.

The reservoirs created by the dams (Lakes Mills and Aldwell) have acted as sediment traps, storing 13.8 and 4.0 million cubic yards of fine-grained sediments. These reservoir traps have starved the lower river, the delta at the river mouth, and the nearshore and beach areas of these sediments, resulting in the transition of nearshore habitat from a predominantly sand into a cobble-dominated system. The interruption of normal shoreline sediment transfer processes also resulted in severe erosion to Ediz Hook, a natural sand spit to the east of the river mouth, and major revetments were installed to protect the Port Angeles harbor.

The release of sediment from behind the dams when they are breached is hypothesized to alter nearshore and marine habitats as well as add to beach protection.

Congress enacted the Elwha River Ecosystem and Fisheries Restoration Act of 1992 (PL102-495) to address these problems. The stated goal of this legislation is, "...the full restoration of the Elwha River ecosystem and native anadromous fisheries." The ***Elwha River Restoration Project*** **(*ERRP*)** will begin with the removal of the two dams on the Elwha River, slated to begin in 2008/2009. Ecological and physical responses to the restoration--such as the effects of restoring sediment delivery processes-- are expected to occur at multiple spatial and temporal scales. Dam removal is hypothesized to provide significant amounts of sediment to the lower river and nearshore marine environments. Sediment delivery will likely take years and is expected to preferentially add finer sediment (sand) to the existing coarse-grained river and nearshore marine habitats. The finer substrates are likely to have major impacts on habitat quality and species responses, and these unknown responses are the focal point of ongoing research.

3.4.3 The Two-Way Traffic of Nutrient Transfer Processes

Nutrients originating from decomposing vegetative and animal matter are an important and necessary part of ecosystem function in Puget Sound, however human activities have accelerated and concentrated many of these processes. Elevated levels of nutrients entering Puget Sound come from point sources such as sewage treatment plants and paper mills, or non-point sources including fertilizers and animal waste. When nutrient traffic loads are excessive, and combine with low circulation rates and topographic barriers, site specific problems may arise, such as the hypoxia conditions in Hood Canal and South Puget Sound (Box citation).

Although freshwater runoff is a primary pathway for nutrient transport from terrestrial to marine environments, the thousands of mobile animals in Puget Sound such as insects, birds, and fish are also effective transfer agents of energy. Moreover, these transfers can occur in both directions and return nutrients from the ocean to freshwater and terrestrial environments. Birds feeding at sea and nesting and roosting on land can transport large quantities of nutrients (Cederholm et al. 1999). Anadromous fish such as salmon also carry nutrients back from the marine environment up into freshwater and terrestrial habitats, enriching food webs far from the sea. The life histories of these Puget Sound species reflect their biological requirements to move back and forth between terrestrial, freshwater and marine habitats depositing substantial quantities of nutrients in the process.

Nutrients from salmon also enter terrestrial ecosystems. The importance of salmon carcasses for plants, insects, bears, and birds has been well documented (Cederholm et al. 1989; Ben-David 1998).

Pacific salmon (Oncorhynchus spp.) accumulate a majority of their body mass in the sea, which is transported to freshwater lakes and streams around the Pacific rim when these fishes return to spawn. As most species of this genus generally die after spawning, the nutrients and organic matter contained in their body tissues and reproductive products are deposited near the spawning grounds. Research has shown that the annual deposition of salmon-derived nutrients contributes to the productivity of freshwater and riparian communities throughout the Pacific coastal region. These nutrients can be incorporated into the stream food web through direct consumption of carcass tissue by fish or invertebrates or uptake of the dissolved chemicals released during decomposition of carcasses (Bilby et al. 2001). Salmon-derived nitrogen comprised from 10% to 20% of the nitrogen in some species of fish and invertebrates in a western Washington salmon stream (Bilby et al. 1996), and reaches much higher proportions in Alaskan systems supporting greater abundances of spawning fish (Kline et al. 1990).

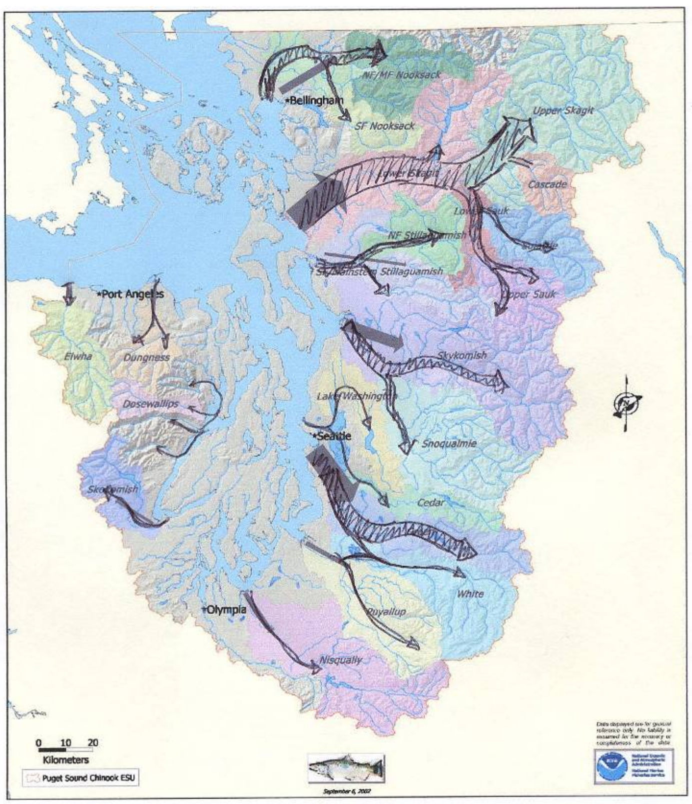


Figure x5. Salmon migrations upstream provide critical nutrients to river ecosystems. Here, width of arrows indicates relative number of Chinook salmon currently migrating into main rivers.
[These are data from Shared Strategy 2005, but the figure is being modified to include all salmon instead of just Chinook]

3.5 Habitats of Puget Sound

"Habitat" describes the physical and biological conditions that support a species or species assemblage and refers to conditions that exist at many scales. An oyster shell provides habitat for some algae and invertebrates, whereas cubic miles of sun-lit open water in Puget Sound comprise the habitat for many planktonic species. Similarly, alpine meadows support lichen and drought-tolerant plants, and riparian corridors along streams are home to shrubby willows and towering conifers. Habitats are created and sustained by long term physical processes such as sedimentation, stream flows, and tidal currents, and can be structured by habitat-forming species such as cedar forests, eelgrass, mussels and bull kelp which are also integral to the distribution and abundance of other species.

Section 3.4 described the connections between terrestrial, freshwater and marine habitats. Within each of these portions of the Puget Sound ecosystem, a complex set of physical processes determine the habitat that is present, and the groups of species that are thus able to thrive. A number of thorough habitat classifications and typologies have been developed for marine and terrestrial environments in the Puget Sound region and are described in Box _____.

Box: Habitat classification information in Puget Sound:

Marine and Estuarine Habitats

- Dethier, M.N. 1990. A Marine and Estuarine Habitat Classification System for Washington State. Natural Heritage Program, Washington Department of Natural Resources. 60 pp.
- Ritter et al. 1996. Puget Sound Intertidal Habitat Inventory 1996: Vegetation and Shoreline Characteristics Classification Methods http://www2.wadnr.gov/nearshore/textfiles/pdf/skagit96.pdf
- Collins and Sheikh 2005. Historical reconstruction, classification and change analysis of Puget Sound tidal marshes. http://riverhistory.ess.washington.edu/project_reports/finalrpt_rev_aug12_2005.pdf
- 1996 PSAT report/workshop Puget Sound Intertidal Habitat Inventory 1996: Vegetation and Shoreline Characteristics Classification Methods

Rivers and Streams

- Beechie, T.J., M. Liermann, E.M. Beamer, and R. Henderson. 2005. A classification of habitat types in a large river and their use by juvenile salmonids. Transactions of the American Fisheries Society 134:717-729.
- Montgomery, D.R. and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin. 109(5):596-611.
- Bisson, P.A., J.L. Nielsen, R.A. Palmason, and L.E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow, pp. 62-73. In Neil B. Armantrout, ed., Acquisition and utilization of aquatic habitat inventory information, Proceedings, Oct. 28-30, 1981. Western Div. Am. Fish. Soc., Portland, OR.
- Bisson, P.A., K. Sullivan, and J.L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Trans. Am. Fish. Soc. 117: 262-273
- Naiman, R. J., D. G. Lonzarich, T. J. Beechie, and S. C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. In P. J. Boon, P. Calow, and G. E. Petts (eds.), River conservation and management, p. 93-124. John Wiley and Sons, New York.
- Rosgen, D. L. 1994. A classification of natural rivers. Catena 22:169-199

Forests/Terrestrial

- Franklin, J.F. and C.T. Dyrness. 1973. *Natural vegetation of Oregon and Washington*. USDA Forest Service, Pacific Northwest Region - General Technical Report PNW-8
- Kruckeberg, A.R. 1991. *The Natural History of Puget Sound Country.* University of Washington Press. Seattle, WA
- USDA Forest Service, Pacific Northwest Region. 1985. *Management of Wildlife and Fish Habitats in Forests of Western Oregon and Washington.* Publication No. R6-F&WL-192-1985. Portland, OR

3.5.1 Freshwater and Terrestrial Habitats

Freshwater and terrestrial habitats of Puget Sound are built around the soils formed by glacial deposits and coniferous lowland forests. Changes in soil, gradient and related variations in precipitation have given rise to diverse plant and animal communities on land. Before European settlement, lowland forests were dominated by western red cedar, western hemlock and Douglas fir, with mixed stands of Douglas fir, Garry oak and Pacific dogwood in drier areas. Today these forest plant and animal groups co-exist in a mosaic with agricultural and urban lands. Considerable attention has been placed on the need to create or preserve habitat of adequate quality, quantity and connectivity for species migration and colonization throughout the Pacific Northwest region (Georgia Basin-Puget Sound Ecosystem Indicators, 2002).

Box: Terrestrial and Freshwater Habitats

Habitat conditions are the prime determinants of the abundance of wildlife -- for both the quantity of species and the number of individuals. Like estuarine, nearshore and open-water habitats, the diverse mosaic of terrestrial and freshwater habitats in Puget Sound directly determines the ability of species to thrive, whether feeding, resting, or breeding.

Insert a photo of an old growth stand

Late successional stands of forest are characterized by decay in living trees, downed woody material, snags, and multiple canopy layers. These heterogeneous conditions support a greater diversity of wildlife habitats than plant communities that have been recently disturbed by fire, flood or cutting. (USDA, 1985) Several terrestrial species utilize unique habitats such as tree cavities, snags and downed logs during some portions of their life cycle.

Large areas of Puget Sound lowlands once contained prairie, oak woodland, and pine forest types, but these are largely relics due to the conversion of land to urban and agricultural uses, invasive species, fire suppression and other disturbances.

The remaining forests in the region provide important habitat for reptiles, amphibians and snails, roost sites for bats, perching and nesting sites for birds, and forage, shelter and travel corridors for deer and other mammals.

Complexity is also essential for freshwater and riparian habitats usable by aquatic, amphibian, riparian, and terrestrial species. Many species are totally dependent on freshwater streams, riparian areas, or wetlands and ponds, such as salmon, beavers, salamanders and frogs. The diverse vegetation layers, ground cover, and downed logs in the riparian zone produce forage material and insects for hundreds of wildlife species, areas for wildlife to breed and rear their young, cover for resting and migration, and thermal shelter from the extremes of summer and winter temperatures.

Insert a photo of a complex stream channel.

Within freshwater streams, the "roughness" provided by large trees and boulders in the stream channel creates pockets of gravel, plunge pools, riffles, overhanging vegetation, and other features necessary for salmon and char to migrate, rest, spawn and rear.

Numerous studies have documented the impact that upland habitat modification can have on downstream, nearshore and estuarine habitats and the slow rate of recovery once these terrestrial habitats have been modified.

3.5.1 Marine and Estuarine Habitats

The steeply sloping sides of Puget Sound allow for only a relatively narrow fringe of vegetated habitat near shore where light can penetrate the water. These habitats support eelgrass, seaweeds, and most marine fish and invertebrate populations at some time during their life cycle. As in other estuaries, the interface between terrestrial or freshwater environments and the marine environment is an important estuarine component; actions in the headwaters affect habitats throughout the marine regions of Puget Sound. Additionally, numerous species continually move back and forth between terrestrial and marine environments. Bald eagles, marbled murrelets and many other bird species utilize marine areas for forage while roosting and nesting on land. Adult bull trout repeatedly transit between freshwater and marine areas; their seaward migration is limited thus placing great reliance for this species on the Puget Sound nearshore. Several species of salmon migrate and rear in these environments at different life stages. When the narrow fringe of habitat along the Puget Sound shoreline is degraded or destroyed, the support system for numerous plants and animals is disproportionately removed.

In aquatic systems, the **pelagic zone** is the part of the open sea or ocean comprising the water column, as opposed to the **benthos** or bottom. The couplings of pelagic and benthic systems are dynamic processes essential to ecosystem function. Just as gradient, soil and precipitation contribute to terrestrial and freshwater ecosystems, physical characteristics such as depth, substrate, exposure, salinity and gradient largely define the plants and animals that can utilize any given area in the marine and estuarine environment.

- **Depth** and its correlates **(temperature and light)** influence the areas that can support primary productivity. In Puget Sound pelagic areas, the euphotic, or lighted zone extends to about 20m in the relatively clear regions of the Northern Puget Sound, and to 10m in the more turbid waters of the South Sound. In shallow nearshore regions, both the water and the substrate can support primary producers. Epibenthic diatoms are found on muddy bottoms; both micro and macroalgae, such as *Fucus sp*. or *Nereocystis* grow on cobble or rocky substrates.

- **Substrate** is another primary contributor to habitat type, and is strongly affected by wave and current **exposure**. Exposed areas do not generally accumulate fine sediments, and thus tend to have clean and mobile sand, or are rocky, either with bedrock or large cobble and boulders. More protected areas accumulate finer sediments, and the most protected areas collect very fine sediment and organic matter, making them muddy or silty.

  Most of the bottom of Puget Sound is comprised of soft sediments, ranging from coarse sands to fine silts and clay. Communities of sediment-dwelling organisms vary with sediment type, water depth, and geographic location throughout Puget Sound. For example, shallow areas are often dominated by eelgrass, while deeper areas are dominated by sea pens (*Ptilosarcus gurneyi*) (insert photograph) and the rich community of predators they support. Deeper sand or mud may contain geoduck clams and other burrowing organisms. Very deep basins contain unusual heart urchins, sea cucumbers, bivalves, and a variety of bottom-dwelling fishes.

  Rocky shores are composed of bedrock or a mixture of boulder and cobble substrates and tend to occur in areas where sediments do not accumulate. Cobble and mixed-substrate sites have communities of diverse bivalves, gastropods, sea stars, brittle stars, and many other invertebrates. Rocky substrates are more stable than sediment-dominated habitats, and the biological communities that develop on rocky shores reflect this. Often, so-called 'ecosystem engineers' such as kelps and mussels are species that themselves influence the physical conditions of local habitats so that they are more hospitable to other species. For example, *Fucus* communities on rocky substrates support a rich array of small grazers and their predators. In lower intertidal and shallow subtidal areas, *Fucus* is replaced by several species of kelp and red algae that support a different and even richer community of grazers and predators (insert photo of Fucus community).

- **Salinity** and the **gradient** from freshwater to brackish and marine waters affect habitat types and the species that can be supported. Deltas and small estuaries within Puget Sound tend to be characterized by soft sediments as well as gradual salinity change. Rooted vegetation including marsh grasses such as invasive *Spartina*, and native species such as *Salicornia* or pickleweed tend to be more common in deltas than in other areas of Puget Sound.

In the greater Puget Sound these physical characteristics generally occur in a transition from north to south, as the influence of the ocean is moderated. Areas to the north and in the Strait of Juan de Fuca are more exposed, and consequently tend to be rockier, less turbid, and more saline. The South Sound tends to be more protected, somewhat shallower, with more sandy and muddy bottoms. Circulation is weaker here, and thus the area is slightly less saline than more exposed regions.

Box___: Examples of Typical Marine and Estuarine Habitat Types of Puget Sound and Some Commonly Associated Species

Left side: Photo of habitat type and typical species present. Right side: Key attributes or functions of each habitat type and where they primarily occur in Puget Sound. Possible layout similar to the layout on page 37 of Chinook recovery plan

Eelgrass Beds *Include a photo of each type and possibly sketch or photo of the typical species in each.*	*Eelgrass beds serve as a refuge for mobile organisms such as crab and small fishes, and forage areas for marine birds, salmon and marine mammals. Eelgrass beds are essential spawning habitat for herring, which support numerous other species in the Puget Sound food web.* *Eelgrass beds occur along 37% of Puget Sound, primarily in the north, and are uncommon in the south Sound.*
Rocky Reefs	*Rocky reefs are characterized by strong currents and tidal action, and the presence of kelps and other large seaweeds. Many organisms in these habitats cling tightly to the rocks or hide in crevices. These areas support benthic suspension feeders and multiple species of fish, including several species of rockfish (Sebastes spp.). Adult rockfish tend to associate with emergent rocky substrates (bedrock, boulders), to which they appear to have high site fidelity.* *Within Puget Sound, 95% of the rocky reef habitat is located in the North Puget Sound basin. [% San Juans?]*
Kelp Beds	*Kelp beds moderate currents in relatively open water areas such as the Strait of Juan de Fuca and provide refuge for mobile organisms and small fishes, which in turn support migrating salmon and marine mammals, as well as forage for marine bird species. Urchins and abalone are among the species found in association with kelp communities, especially in northern Puget Sound regions; both species have declined sharply due to human removals for food*
Tide Flats	*Tide flats, such as river deltas and protected coves, are characterized by weak circulation, gradual slopes and sandy or muddy substrate. They provide habitat for organisms in the detritus-based food webs that support most of the biomass in Puget Sound. Numerous species of burrowing invertebrates and fish utilize these areas during some portion of their life cycle. Higher zones may have large populations of burrowing mud shrimp, clams, introduced oysters, and a variety of snails and crabs. Microalgae (diatoms and other species) often cover the surface of such mudflats and can be highly productive. Tide flats are also important forage areas for marine birds at low tide.*
Saltmarsh	*Rooted marsh grasses such as Salicorna or pickleweed, are often associated with the sediment deposits at river deltas. Marsh plants are essential to the development of nearshore food webs, including those important to migratory birds. These vegetated estuarine habitats are also used extensively by crabs, shrimp and juvenile fishes. However, it should be noted that areas infested by Spartina are not usable by most native species.*
Subtidal soft sediments	*Soft sediments, ranging from coarse sands to fine silts and clay, are the predominant subtidal substratum in Puget Sound. While a diverse array of large invertebrates, including snails, seastars, and sea cucumbers, live on the sediment surface, a rich variety of burrowing and tube-dwelling microscopic organisms dwell within the sediments, including marine worms, bivalves and snails, crustaceans, seastars, sea urchins, sea cucumbers, and an assortment other taxa. Communities of these sediment-dwelling organisms differ with different sediment type, water depth, and geographic location throughout Puget Sound. They provide a rich food source for an abundance of bottom-feeding organisms, and serve as indicators of environmental quality.*

Open Water/ Pelagic	*Open waters of Puget Sound are characterized by variable light, current and temperature conditions. Open water/pelagic habitats support plankton communities including the dispersing larvae of many species whose adults occupy other habitats. These in turn support open water fishes.*

3.6 Puget Sound Species and Their Interactions

One of the most striking features of the Puget Sound Ecosystem is the diverse and abundant flora and fauna it supports. Although a complete census of many taxonomic groups (or 'taxa') has not been accomplished, Puget Sound hosts more than 100 species of sea birds, 200 species of fish, 15 marine mammal species, hundreds of plant species, and thousands of species of invertebrates (Armstrong et al. 1976; Thom et al. 1976; Canning and Shipman 1995). The array of species found in Puget Sound reflects its high productivity, the wide diversity of habitats present, and the unique geographic location at the interface of "northern" and "southern" ranges for many species. These species do not exist in isolation, but rather interact with each other in a variety of ways: they eat and are eaten by each other; they serve as vectors of disease or toxins; they are parasitic; and they compete with each other for food, habitat and other resources.

3.6.1 Who Eats Whom in Puget Sound Food Webs?

Although considerable information is lacking on species interactions between Puget Sound organisms, the best understood elements are the interactions that occur in the food webs, particularly those of the nearshore environments (Simenstad et al. 1979). Approaches to investigating food webs include the analysis of energy flow between species based on measurements and calculations, incorporating observations of species eating one another or competing for food or space into network relationships or manipulation experiments aimed to identify food web interactions. Importantly, food webs are tailored to their purpose, much like maps are. A map of bus routes looks very different than a map that describes the topography of the area, for example. Thus, food webs can depict the flow of energy between species or the strength of interactions between them. The level of detail they present for particular species may also vary – on that is very detailed for salmon, may be much less detailed for deep-water bivalves.

The following general overview of the Puget Sound marine food web outlines the primary energy inputs to the system, and typical pathways through which that energy flows up through the ecosystem to humans and other top-level consumers. A simplified view of the various pathways is presented in Figure ____ (energy pathways figure,). Unfortunately, the pathways of the food web also act as routes for the transfer or accumulation of toxins.

Food webs change both in time and space due to variation in stratification, prey availability, organic matter source availability and quality, and other local and regional conditions. In addition, some species occupy multiple places or play multiple roles in the food web depending on their life stage, size, habitats they occupy, and time of year. Juvenile crab zoea (photo), for example, live in the water column and are planktivorous, while adult crabs are bottom scavengers and predators.

3.6.1.1 Energy Inputs

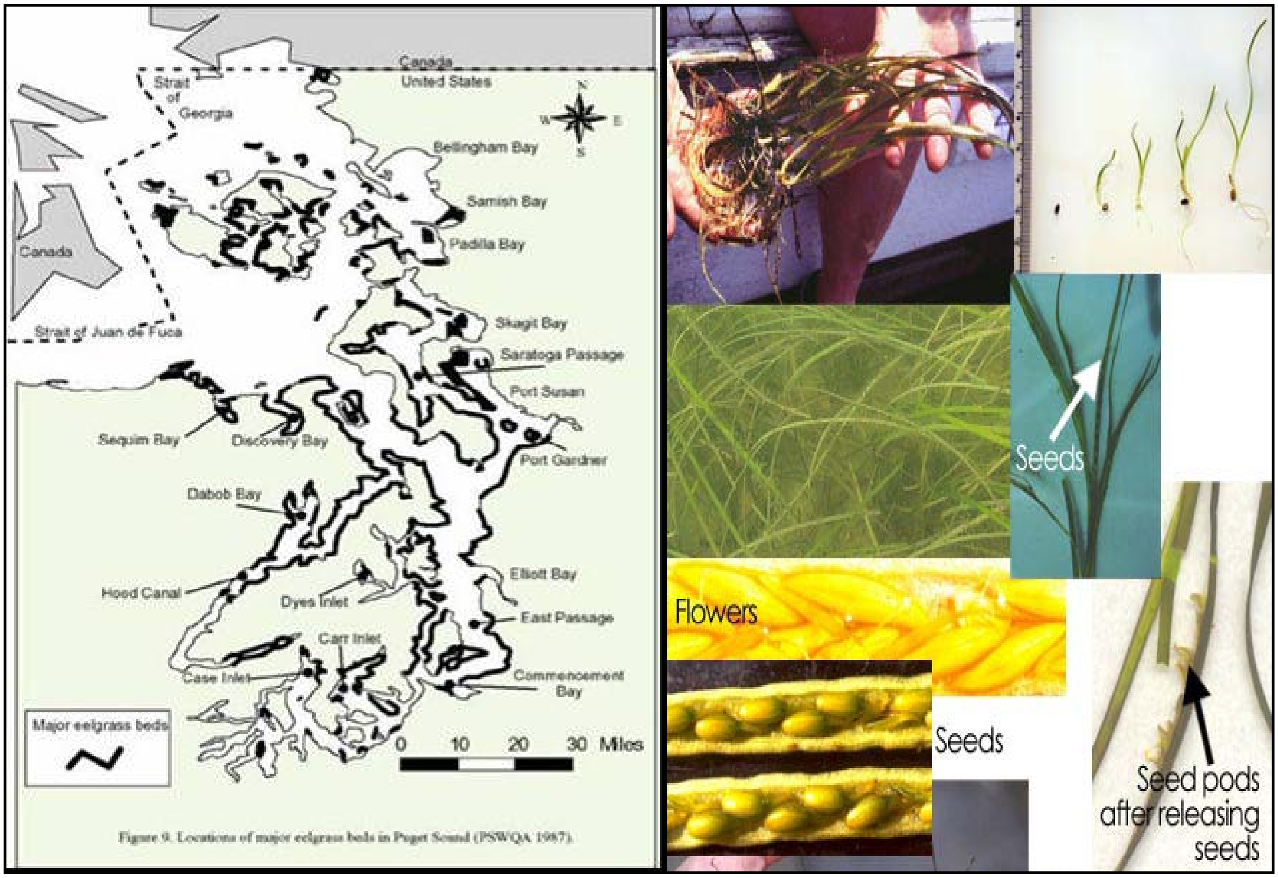
During the past 50 years, energy transfer processes in Puget Sound have gone through major transformations. Tideflats, a key venue for the exchange of energy in the food web through transfer of nutrients and sunlight, have been modified dramatically in Puget Sound. Additionally the tremendous increase in human population around the Sound has increased the input of nutrients in the form of sewage, with corresponding changes to the organisms that utilize them throughout the food web. These changes point to the need to look at Puget Sound with a wider ecosystem perspective, beginning with attention to the species that form the basis of the food web. Energy inputs to the Puget Sound food web originate from marine primary producers, detritus, and from terrestrial or freshwater systems.

- Primary producers. Primary producers are the plants that employ sunlight to convert organic and inorganic nutrients into living tissue. The major classes of producer organisms in Puget Sound are phytoplankton, sediment-associated microalgae, and rooted or attached algae and vascular plants in the Sound, freshwater and on land. Each type of producer plays a different role in Puget Sound, and its level of importance in food webs varies among the nearshore and offshore marine habitats and in different terrestrial environments.

  Phytoplankton are largely produced in the more open waters of Puget Sound, both nearshore and offshore. Populations in Puget Sound consist of mainly large-sized phytoplankton of two major groups: diatoms and dinoflagellates, with diatoms accounting for most of the biomass. These single-celled plants are eaten directly by zooplankton and some benthic filter feeders (*e.g.*, oysters). Phytoplankton abundance and distribution is highly heterogeneous or “patchy” both spatially and temporally, and is linked to the degree of stratification, light availability, turbidity and nutrient availability in particular areas. This variability in phytoplankton density and distribution in turn affects the distribution and abundance of the various phytoplankton consumers (e.g., benthic filter-feeders, zooplankton) as well as their predators.

  Attached or rooted plants are found in many of the habitats of Puget Sound (Table ___, habitat and associated species), and factors such as substrate, light penetration and salinity largely determine the species composition in a particular area. Some of these “attached” plants are single-celled algae or diatoms that adhere to benthic substrates, or are motile within sediments and are typically eaten directly by grazing invertebrates and fish. The most familiar attached plants, however, are larger taxa; these include macroalgae such as bull kelp, which are found in the less turbid marine waters of Admiralty Inlet, the Straits of Juan de Fuca, and the San Juan Islands, and rockweeds (*Fucus spp.),* which are abundant on rocky shores throughout the region, where they support a rich array of small grazers and their predators. Familiar vascular plants are eelgrass *(Zostera marina*; Box 3.6.2) and the salt-tolerant marsh grasses found in estuarine environments. The majority of these macrophytes are not eaten directly by grazers, but contribute to the food web through the detrital pathways. Several introduced and invasive species, most notably the salt marsh cordgrasses *Spartina alterniflora, S. anglica* and the eelgrass *Zostera japonica* remain in Puget Sound. However efforts to eradicate or control the spread of some of these species have been successful at some site-specific locations (PSAT, 2005).

[Box 3.6.2. Eelgrass distribution in Puget Sound and its natural history.]



- Detritus: When estuarine and marine macrophytes die or senesce (or terrestrial plant material is washed in), they are colonized by microbes, including bacteria, protists and fungi that break down and transform the organic matter into a form where it can be used again by producers. This non-living organic material with its associated microbial community is termed detritus. These microbes form the basis of most estuarine and nearshore marine detrital food webs and are eaten by an extremely wide variety of consumers, including gammarid amphipods, ostracods, crabs, holothurians, insect larvae, copepods and cumaceans. This consumer pathway is a very important trophic pathway in the nearshore areas and deep benthic habitats of Puget Sound.

  [Placeholder for a possible box on detritus.]

Terrestrial and freshwater inputs: The marine food web in Puget Sound is not isolated, but relies on nutrients and energy from terrestrial and freshwater sources as well as marine sources (see sections 3.3-3.4). Organic material from terrestrial and freshwater environments washes into Puget Sound and is consumed directly by marine organisms. Anadromous species may directly consume freshwater or terrestrial organisms in freshwater and estuarine habitats. In addition, animals such as some marine birds, salmon and other species that are not restricted to marine habitats serve as transfer agents of marine nutrients and energy to terrestrial or freshwater habitats.

Table ________. Example habitats in the Puget Sound and some of their more commonly associated species.

Habitat	Energy Inputs	Invertebrates	Vertebrates
Sandy and muddy bottomed habitats	Detritus, benthic diatoms	Bivalves, polychaetes and other worms, crabs, shrimp, copepods, amphipods, isopods, sea cucumber; sea pens, hydrocorals in deeper areas	Sculpin, flatfish, juvenile sand lance and herring in shallow tide flats, sand lance, shorebirds, gulls
Coarse substrate nearshore habitats	Micro and macro-algae, detritus	Bivalves, copepods, amphipods, shrimp, echinoderms	Rock sole, juvenile salmonids, sculpin, cabezon, shorebirds, merganser
Rocky nearshore habitats	Macro-algae, sessile micro-algae, detritus	Anemones, urchins, sea stars, chitons, sponges, gammarid amphipods, mussels	Gunnels, sculpins and pricklebacks in shallows; lingcod, greenling, rockfishes in deeper and reef areas. Shorebirds and gulls. Sea lions and harbor seals.
Eelgrass beds	Eelgrass, detritus	Gammarid amphipods, flatworms, snails, isopods, amphipods, copepods, bivalves	Pacific herring, juvenile salmon, juvenile flatfish, Canada goose, snow goose, American coot
Vegetated estuarine habitats	emergent and woody wetland vegetation, detritus	copepods, amphipods, isopods, cumaceans, crabs, bivalves, snails	sculpins, gunnels, juvenile salmonids, juvenile flatfishes, great blue heron, dowitchers, yellowlegs, other shorebirds, pintail, mallard, other ducks
Kelp beds	Bull kelp, detritus	Chiton, limpets, abalone, harpaticoid copepods, gammarid amphipods, some crabs, sponges and bryozoans	Yellow tail rock fish, lingcod, Pacific sand lance, herring, Puget Sound rockfish, sea lions
Open water habitats	Phytoplankton	Calanoid copepods, gammarid amphipods, other crustacean larvae, adult crustaceans, larvaceans, jellyfish,	Pacific herring, sand lance, salmonid juveniles and adults, fish larvae, orca, Dall porpoise, auklets, grebes, murres
Offshore benthic habitats	(Reliant on detritus, more)	To be developed	To be developed

<u>3.6.1.2 Herbivores and detritivores.</u> Many consumer organisms in Puget Sound are both herbivores and detritivores; zooplankton and benthic invertebrates that are scavengers, herbivores or detritivores are considered jointly in this section. Some of these organisms can be predatory as well.

Hundreds of invertebrates and fish species have a planktonic larval stage that eats plants and occupies the nearshore and offshore pelagic waters of Puget Sound. While many species of invertebrates (e.g., copepods) complete their entire life cycles in the water column, many cnidarians, arthropods, mollusks, echinoderms, annelids, tunicates, and fish species are present in the plankton for only a portion of their lifecycle. Many zooplankton are suspension-feeders, dependent on phytoplankton for food. They are thus an important step in the pelagic part of the food web, transforming the organic matter derived from primary production into food for invertebrates, fish, birds, and mammals. The distribution and abundance of zooplankton is probably correlated to changes in distribution of phytoplankton (Strickland, 1983), but quantitative studies of the zooplankton assemblage in the Puget Sound region are rare and quite limited in scope.

The benthic habitats of Puget Sound are home to thousands of species of herbivorous/detritivorous invertebrates. These species include those that live in the bottom (infauna) and on the surface of the bottom (epifauna) and that may be motile or sessile (Kozloff 1983). The adult stages of a number of benthic species are economically important and include native species such as pandalid shrimp (*Pandalus* spp.), Dungeness crab (*Cancer magister*), geoduck clam (*Panopea abrupta*), and butter clam (*Saxidomus giganteus*) as well as non-native species such as Japanese littleneck clam (*Tapes philippinarum*) and Pacific oyster (*Crassostrea* gigas). These benthic invertebrates also use a variety of feeding methods, including filter or suspension feeding (mussels, clams, scallops, oysters, worms, and barnacles) and grazing (sea urchins, snails, limpets and chitons. Detritivorous invertebrates include sea cucumbers, crabs, amphipods, and isopods. These taxa are preyed on by other invertebrate, fish, mammal and bird species as adults or as eggs and larvae when vast amounts are released during reproduction.

<u>3.6.1.3 Mid-level consumers.</u> A variety of animals, including invertebrates, fish, mammals and birds consume the suspension-feeders, filter-feeders, grazers and detritivores that serve as a link between the primary producers and detrital pathways and the upper levels of the food web.

The juvenile and adult stages of many fishes and bird species, are also important mid-level consumers. The diet of these species in Puget Sound can vary dramatically in breadth and complexity and can contain prey from many different habitat types. For example, some juvenile Chinook salmon have eaten (at any one time) terrestrial insects, aquatic insects, amphipods, copepods, polychaetes, fish larvae, and crab zoea (Brennan et al. 2004).

Planktivorous fish feed in water column habitats associated with nearshore and open marine waters of Puget Sound. Based upon their abundance/biomass, Pacific herring, juvenile salmon, juvenile Pacific sand lance, and northern anchovy are probably the most important planktivores. Other noteworthy species in this group include several important rockfish species (black, canary, widow, and yellowtail rockfish) and some species of marine birds that forage on amphipods and euphausiids (Bonaparte's Gull).

However, a wide variety of species of copepods, crab larvae, and euphausiids or krill are usually elements of planktivore diets (Strickland 1983). Diets of planktivores can vary over relatively small spatial and temporal scales, which is consistent with the bloom and bust dynamics of their prey (barnacle larvae, copepods and crab larvae).

Pacific Herring** (Clupea pallasi): **A Vulnerable Member of the Food Web Hall of Fame

Pacific herring are a favorite prey of many Puget Sound species. Their eggs and larvae are eaten by walleye pollock, juvenile salmon, invertebrates and at least 14 species of ducks and gulls. Adult herring are eaten by salmon, seals, sea lions, killer whales, dogfish, hake, halibut, sablefish, cod and many species of marine birds including loons, grebes, cormorants, herons, mergansers, terns and puffins. Studies of the diets of fish off of the west coast of Vancouver Island indicated that herring comprise 71% of lingcod, 62% of Chinook salmon, 58% of coho salmon, 53% of Pacific halibut, 42% of Pacific cod, 32% of Pacific hake, 18% of sablefish, and 12% of dogfish diets (Environment Canada 1998).

Pacific herring usually spawn at night in the shallow subtidal zone, depositing their eggs primarily on eelgrass, but also utilizing kelp, brown and red algae or occasionally, gravel. Their use of shallow subtidal areas for spawning makes them susceptible to changes in currents and wave action resulting from shoreline development. Eighteen recognized stocks of Pacific herring spawn in Puget Sound's protected bays and inlets.

A biological status review of Pacific herring was conducted in 2001 by NOAA Fisheries (Stout, et al.). The reviewers determined that Puget Sound herring populations were not distinct enough from the more abundant herring populations of the Georgia Basin to merit a listing under the Endangered Species Act; however they recognized that herring populations in north Puget Sound and Puget Sound proper may be vulnerable to extinction. The reviewers expressed caution that the conservation of local populations of Pacific herring is essential for the viability of coastal fisheries, and repercussions to marine bird populations from their demise could be severe.

Photo to be included.

In contrast to the planktivorous fish, there are many species of birds and fish that eat mostly invertebrate food items found on or in the benthos. From a species perspective, there are far more species that fall into this trophic group than in the other groups. What any one species eats depends upon many factors including varying environmental conditions, habitat (e.g., deep vs. shallow), and morphology (e.g., bill size and shape). Shorebirds such as plovers, yellowlegs, killdeer, and many migrating sandpiper species forage in the sediments left exposed by the ebbing tide, and this is a common scene in sand and mudflats around Puget Sound. Flatfish often eat the tips of bivalve siphons. And, there are the species that eat their prey off the substrate surfaces such as oystercatchers, gulls and scoters. Some of the abundant surfperches such as shiner perch primarily forage on organisms that occupy substrate surfaces.

3.6.1.4. Top-level predators

Fishes, birds and mammals (including humans) serve as top-level carnivores in the Puget Sound ecosystem. With the exception of humans, these organisms have a diet that consists almost entirely of fish or other vertebrates. Food habits of some top-level predators, such as orcas, throughout the Sound have been studied. Pacific herring is widely considered to be a key species in the Puget Sound food web due to its abundance and prevalence in diets of many species and its role transferring primary producer biomass into higher trophic levels.

Fish predators at this trophic level include larger size classes of Chinook salmon, spiny dogfish, some rockfish species, and large pelagic and rocky reef species. Populations of most species of rockfish in Puget Sound have declined sharply, and most now are conservation targets (PSAT 2004). The condition of many salmon populations is regular news in Puget Sound; because of their use of a huge landscape, factors affecting their abundance extend beyond the waters of Puget Sound.

Common bird species in this trophic level are piscivorous (fish-eating) birds such as Rhinoceros Auklet, Pigeon Guillemot, Common and Red-throated Loons, Horned Grebes, and Marbled Murrelets, Glaucous-winged gulls, and Caspian Terns (Nysewander *et al.* 2001, Bower 2004; Lance and Thompson 2005; Litzow *et al.* 2004). In Puget Sound, these birds prey primarily on small pelagic fish (Pacific herring, Pacific sand lance, salmonids, threespine stickleback). One striking feature about the birds that prey on pelagic fish is that many of them have experienced dramatic declines in abundance. Bald Eagles will scavenge from spawned out adult salmonids, but are also predators of many of the piscivorous bird species.

Marine mammals that eat primarily fish include harbor porpoises and California sea lions. Harbor seals, the most common pinniped in Puget Sound, eat mostly schooling fish such as herring as well as squid, pollock, hake, smelt, midshipman, and sculpin. Top-level mammalian predators include humans, orcas, seals and other marine mammals. Killer whales include both the piscivorous ecotype that eats largely adult and subadult salmon and the marine mammal eating ecotype that eats such species as harbor seals. People, of course, forage at all levels of the food web on prey ranging from algae, eggs and larvae, invertebrates of all sizes, to large food fish such as salmon and rockfish.

3.6.1.5 Food Web Linkages

The relationships between these species and "levels" in the food web is not strictly linear (Figure – food web) as some species (such as humans) eat at many levels. In addition, because many species rely on food or habitat from similar sources, the relationships between them can be quite complex. The abundance of sea otters (a top-level predator), for example, has been shown to have an indirect effect on the distribution and abundance of fishes dependent on kelp forests (Box – Sea Otters).

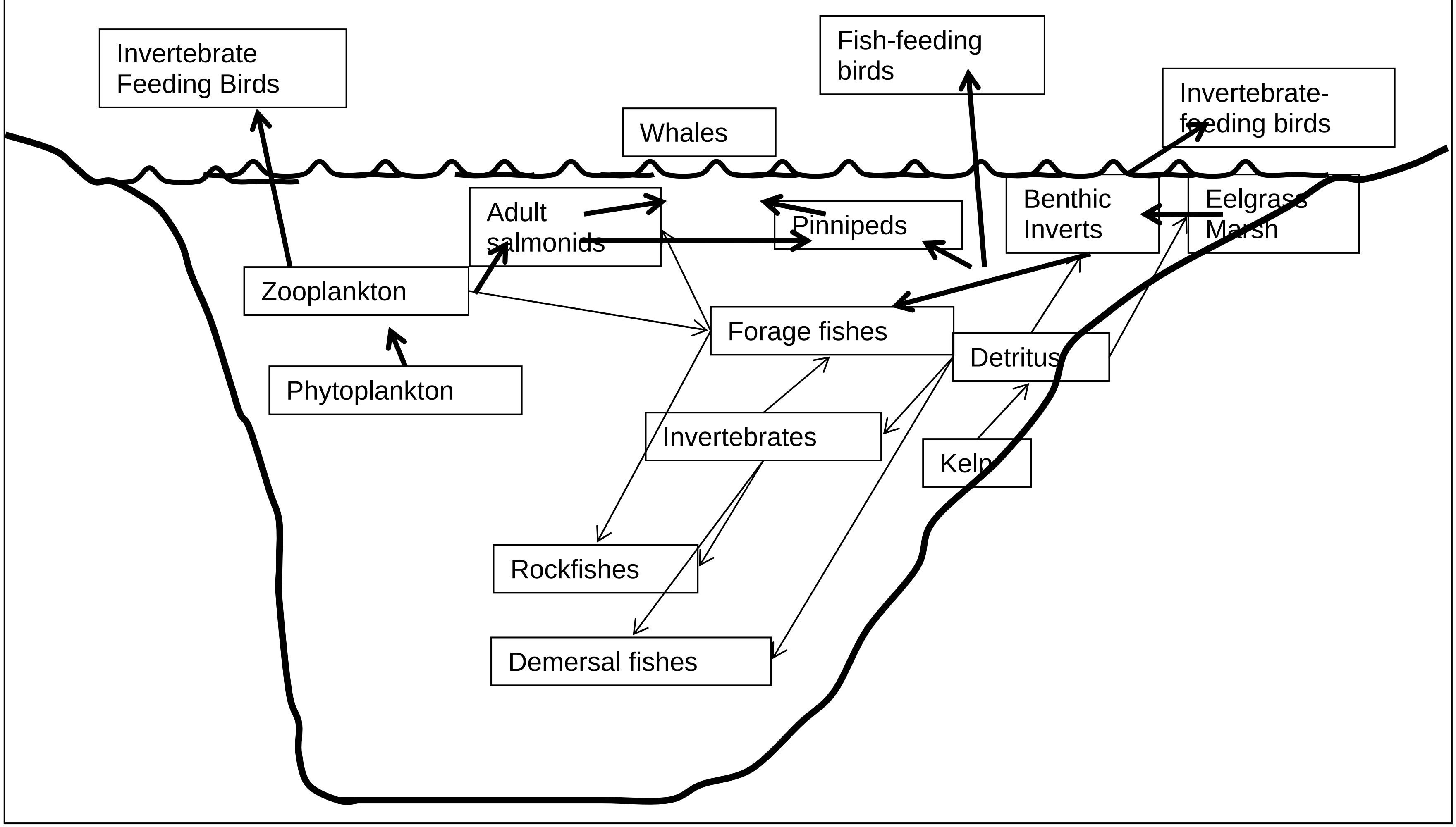
A Trophic Cascade: Sea Otters, Sea Urchins, Kelp Forests and Kelp Forest Fishes

A change in the abundance of a top level predator such as sea otters *(Enhydra lutris)* has cascading effects to the structure of the food web. Sea otters consume herbivorous sea urchins *(Strongylocentrotus polyacanthus)* which consume bull kelp *(Nereocystis luetkeana)* and other fleshy algae. By keeping the urchins in check, the sea otters allow kelp forests to thrive and provide three-dimensional habitat and nutritional fuel for numerous other species. Studies of the fluctuating population levels of sea otters have shown a close relationship to fish species such as rock greenling *(Hexagrammos lagocephalus)* that use the kelp forests for feeding, shelter and egg laying. In areas with high density sea otter populations, kelp forests were dense and abundant populations of greenling were present, while the opposite pattern was observed where the sea otters were rare (abundant urchins, sparse kelp forests, and relatively few greenling). (Reisewitz et al., 2006)

Once hunted to near extinction for their fur, sea otters have been influenced by human and oceanic factors that result in population fluctuations, with ramifications to the food web. As the sea otters foraged in the early stages of recovery from hunting, sea urchins were their primary food due to their abundance and accessibility. As the sea urchin populations declined, competition patterns within the plant communities became prominent, populations of some fish species increased, and the sea otters foraged on a wider range of fish species (Estes, et al., 1978).

In addition, there is no single food web in this ecosystem. Rather, there are many marine food webs that reside in the soft-bottomed nearshore, in rocky-bottomed areas, in habitats dominated by eelgrass or kelp, and in pelagic areas as well. Similarly, there are alpine food webs, those that occur in mid-elevation forested habitats, and freshwater aquatic food webs, to name a few terrestrial environments. The food webs in each of these areas are not discrete and independent, but rather are highly interconnected, both by organic matter sources, physical proximity, exchange of water, and organisms that change habitats during the course of their life cycles.

Figure in development – Puget Sound food web (currently conceptual and incomplete).



3.6.1.6 Food web connections beyond the marine areas of Puget Sound

In the same way that Puget Sound physical processes are linked to ocean, freshwater and terrestrial environments (sections 3.3-3.4), the Puget Sound food webs described above do not exist in isolation, and are connected by organisms that that reside or migrate outside of Puget Sound marine waters. Changes to the abundance and relationships of species within Puget Sound may be affected by changes in the open ocean or terrestrial landscape.

For example, many waterbird species, including loons, grebes, scoters, murres, and murrelets move to the protected waters of Puget Sound for the winter and feed on Puget Sound species, thus are transient members of the food web. Recent studies in Puget Sound and surrounding waters have shown 50-95% declines in populations of many marine bird species during the past 20 years (Nysewander *et al.* 2001, Bower 2004). The species that have shown the most alarming declines (80-95%) are diving birds such as common and red-throated loons, western, red-necked and horned grebes, and marbled murrelets, all of which specialize on schooling pelagic fish (Nysewander *et al.* 2001, Bower 2004). Marked declines have also been observed in summer breeding populations of fish-eating seabirds. For example, common murres declined by 83% in the early 1980s, and numbers have never recovered (Manuwal et al. 2001). Moderate declines (50-60%) have also been observed in a variety of birds that are less dependent on pelagic forage fish because they can also subsist on benthic or demersal fishes (e.g., cormorants and guillemots) and sub-tidal or intertidal invertebrates (e.g., gulls and scoters). Declines in these waterbirds may reflect declines in species that are harder to count, such as small benthic or pelagic fishes. Forage fish species may be affected by changes in habitat and physical processes both within and outside of Puget Sound, with ramifications to food webs across broad areas.

The movements of transient and migratory species also connect Puget Sound with the rest of the North Pacific. Salmon are an outstanding example of these complex food web linkages as they rear in freshwater and estuarine environments, migrate to marine waters and the open ocean, and return to transfer nutrients to terrestrial species such as eagles and bears. Additionally, salmon can simultaneously occupy multiple places in the food web depending on their life stage, size, habitats and time of year. Some marine mammals such as sea lions and orcas spend just a portion of the year in the waters of Puget Sound, migrating to other areas at other times of the year.

3.6.2 Competition

In addition to the transfer of energy up a food chain, other species interactions can be important to the functioning of the freshwater, estuarine, and marine communities that comprise the Puget Sound ecosystem. Competition within and among species can influence food web dynamics and species distribution and abundance.

For example, on the rocky habitats of Puget Sound, the survival of species can depend on their ability to adapt to the vagaries of wind and waves, their ability to compete for space, and their ability to outgrow their predators. Starfish *(Pisaster ochraceus)* prey on mussels *(Mytilus spp.)* in this rocky, intertidal zone, yet these species can be found living in close proximity for decades. Where starfish are dense and have been present for a long time, there are no large mussels and local species diversity is low. However, if the mussels can survive for a few years at the high edge of the intertidal zone, or by accident or ineptness on the part of their predators, they become too large for the starfish to eat, reproduce disproportionately, and develop complex, multi-dimensional colonies that serve as habitat for other, smaller species. The ability of the mussels to use the limited space available on rocky shorelines also enables them to outcompete other species, such as barnacles, that vie for the same habitat areas. Eventually, because of physical disturbances and occasional predation by starfish, patches of different-aged mussel beds arise across a rocky shore, giving rise to a mosaic of habitat and species diversity. This phenomenon is not unlike the process of forest succession, whereby seedlings that survive to a certain threshold become too large for grazing predators, eventually giving rise to canopies that serve as habitat for other species.

<u>3.6.3 Other Species Interactions -- Disease, Parasites, Bio-contaminants and the Transfer of Pollutants</u>

Food web linkages and structure can serve to transfer more than energy. Parasites and pathogens, both endemic and introduced, can affect the health of marine populations and human populations. A variety of parasites, pathogens and biotoxins pose a threat for the upper trophic levels of Puget Sound. However, little is known about the transfer mechanisms in natural settings or as a result of artificial propagation.

Most notably for human health and management, toxins can be accumulated and concentrated at higher trophic levels. Both naturally occurring toxins, such as those resulting from harmful algal blooms (box___) and manufactured pollutants such as pesticides and polychlorinated biphenyls (PCBs) are transferred and concentrated by organisms in the Puget Sound food web. Food web dynamics can also contribute to the geographic movement of toxins. As organisms or their predators move from contaminated areas, toxic substances may be distributed to less polluted areas.

Harmful Algal Blooms (HABs) in Puget Sound

Out of the thousands of species of microscopic marine algae in the world, a handful of species occur in Puget Sound that can produce toxins that are harmful to humans and wildlife. These toxic effects are the most pronounced during periodic "blooms" when these naturally-occurring species proliferate due to a combination of warm temperatures, sunlight and nutrient-rich waters (described in section 3.3. The algae are ingested by several species of shellfish, such as clams, oysters, mussels and geoduck, which concentrate the toxins. Three types of HABs in Puget Sound are closely monitored by state agencies and tribes for issuing public health warnings, and long term trends are being evaluated in a number of studies: [insert photos or drawings of these species]

Paralytic Shellfish Poisoning is caused by toxins produced by the marine alga *Alexandrium.* Although the toxin does not harm shellfish, it can induce serious neurological disorders or even death when ingested by humans or marine mammals. The earliest documented case on the West Coast was in 1793, when 5 members of Vancouver's expedition became ill and one died after eating mussels from the coast of British Columbia. In Washington State, illnesses and deaths in the 1940s launched long term monitoring programs that have recently been assessed for geographic and temporal changes in PSP incidences. A geospatial map of the first shellfish closures or PSP event in each Puget Sound basin suggests that over time, toxigenic *Alexandrium* cells have been transported from northern to southern Puget Sound, with the initial "seed" population of cells in Washington State likely originating from the inland or coastal waters of Canada (Trainer et al., 2003).

Domoic Acid Intrusion into Puget Sound: The marine alga *Pseudo-nitzschia* produces a toxin called domoic acid, and was first documented in razor clams on the west coast of Washington in 1991 at levels above U.S Food and Drug Administration action levels. The toxin causes Amnesic Shellfish Poisoning and interferes with nerve signal transmission; in severe cases it can cause short term memory loss, repiratory distress and even death. Following emergency closures, a domoic acid monitoring program was established, and from 1991 to 2003, domoic acid closures remained an outer coast problem. However, in September, 2003 a bloom was detected on Marrowstone Island in Jefferson County and domoic acid was detected at low levels over a wide area, as far west as Port Angeles, as far east as East Whidbey Island and as far south as Port Ludlow (Bill et al. 2006). In September and October 2005, unacceptable levels of domoic acid were measured in commercial mussels from Penn Cove and in clams from Holmes Harbor, and numerous other shellfish species were affected in other areas including Saratoga Passage and Sequim Bay. If domoic acid closures follow the same southward migrating trend as PSP closures have in the past several decades, much of Puget Sound will be impacted by this toxin in the near future.

Fish kills: *Heterosigma akashiwo* is a bloom-forming species, usually rare in the plankton, but capable of forming dense blooms that are often associated with low salinity surface waters. It is not known to be toxic to humans, but can cause extensive fish kills, especially of cultivated salmonids, but wild fish may also be affected. It has apparently been present in Pacific Northwest waters at least since the 1960s and has been associated with fish kills since 1976 (Taylor and Horner 1994). Kills of finfish reared in net pens have also been caused by several species of diatoms, including *Chaetoceros convolutus* and *C. concavicornis*, since the early 1960s.

Nontoxic algal species: Several other species of algae that are found in Puget Sound waterways can cause damage to fisheries or result in nuisance water discolorations. A summary of these species and their effects is found in Horner et al. (1997).

3.6.3.1 Effects of pathogens and toxins on marine species

Orcas and seals in Puget Sound are among the most contaminated marine mammals in the world; relatively high levels of PCBs and flame retardant chemicals (PBDEs) have been found in orcas and harbor seals throughout the Puget Sound and Georgia Basin. Even though U.S. manufacturers stopped producing DDT and PCBs in the 1970s, both chemicals are still found in the environment because they break down slowly and they accumulate in the fat of organisms. A position at the top of Puget Sound food webs has made harbor seals the unfortunate indicators of persistent contaminants in the Puget Sound food chain because toxins, such as PCBs and DDT, accumulate in their abundant fat layers. A recent scientific study found levels of PBDEs in Puget Sound orca whales that were 2-10 times higher than levels found in other whales around the world. Toxins that accumulate in the sediment make their way up through the detrital food webs of Puget Sound into top consumers. The Puget Sound Update and State of the Sound Report (PSAT; 2002, 2005) describes these issues in detail.

Begin Box

Pollution in Puget Sound

Throughout the United States, pollution is widely recognized as one of the most significant and emerging threats to coastal ecosystems. This is particularly true of Puget Sound, where decades of nearshore industrial activity have left a legacy of persistent and bio-accumulative chemicals in sediments and the estuarine food web. Pollution is not merely a problem of the past, however. Today, simply driving a car can pollute the Sound. Roads, highways, parking lots, residential homes, lawns, and golf courses all leave a chemical signature on the landscape. These chemicals are mobilized by rainfall and transported via stormwater runoff to receiving waters and sediments in the marine environment.

Toxic chemicals have been the focus of research and monitoring efforts in Puget Sound for several decades. In the 1970s and 1980s, the attention of early investigators was mostly drawn to a few toxic "hot spots" around the region. These were generally areas that had been heavily polluted by specific industrial activities, including several sites that were targeted for cleanup under the Comprehensive Environmental Response, Liability, and Compensation Act, also known as Superfund. Much of this work focused on assessing the environmental health of species living in or near contaminated sediments. Among their many discoveries, researchers found that sediment-associated flatfish from polluted sites had high incidences of liver disease and cancer. Numerous additional adverse health effects have since been documented in fish exposed to pollution. These include, for example, developmental defects, reduced growth, increased disease susceptibility, and reproductive abnormalities.

[insert a photo of the pre-spawn salmon mortality along with the caption:]

> *Adult coho salmon returning to spawn in a Seattle-area urban creek in the fall of 2005. This female died prior to spawning as is evident by the complete retention of eggs. This phenomenon has been termed "pre-spawn mortality" and has been consistently observed around the region for several years. At present, the weight of evidence indicates that these recurrent fish kills are caused by polluted stormwater. Photo by Sarah McCarthy, Northwest Fisheries Science Center.*

Chemicals such as PCBs and DDT, which were banned in the 1970s, are often referred to as "legacy contaminants" because of their long term persistence in the environment. The list of persistent pollutants also includes mercury, dioxins, and brominated flame retardants (PBDEs) that originate from modern industrial and manufacturing activities. These chemicals are picked up from sediments by benthic (bottom-dwelling) organisms and transferred up the food chain to species that frequent open waters and freshwater and terrestrial areas. As they move through the food web, concentrations may become more acute--a process known as "bio-magnification," and pose an important health risk for top level feeders such as salmon, raptors, marine mammals and humans.

Growing evidence suggests that toxic contaminants are not confined to a few specific hot spots associated with industrial uses. Treated municipal sewage contains a complex mixture of personal care products, caffeine, endocrine-modulating chemicals (e.g. birth control pills), antidepressants and other pharmaceuticals. Airborne particulates from the fuel emissions of cars, trucks and stationary sources wash into rivers, streams and marine waters, and upload back into the food web. In 2001, an estimated 7.7 million pounds of toxic chemicals were released into the air in the Puget Sound basin from stationary sources alone. (not including mobile sources such as cars or trucks). Hundreds of oil spills (major and minor) occur annually.

In response to ecological and human health concerns, the Puget Sound Ambient Monitoring Program (PSAMP) has been documenting the levels of persistent pollutants in different components of the marine ecosystem for more than 15 years. This long-term monitoring effort has shown that bio-accumulative contaminants are present at all levels of the food web, and at much higher concentrations in Puget Sound (and particularly in southern Puget Sound) than in the Georgia Basin or the coastal northeast Pacific Ocean. Trends in the levels of toxic contaminants for several indicator species are discussed in the PSAMP reports as well as the "State of the Sound" report (PSAT, 2005), and the 200_ series by the Seattle Post-Intelligencer, "Our Troubled Sound" (http://seattlepi.nwsource.com/specials/sound/). A few indicators include:

- Concentrations of persistent organic pollutants are higher in the blubber of southern resident killer whales than in other North Pacific orcas. The accumulation of these compounds may cause immune suppression, reproductive dysfunction, and thyroid disruption in these top Puget Sound predators.

- Dissolved metals such as copper from roads and other impervious surfaces have been shown to interfere with the ability of juvenile salmon to detect and respond to predators.
- Levels of PCBs in herring, a key mid-level species in the Puget Sound food web, are several-fold higher in central and southern Puget Sound than those from sites in the Georgia Basin. Recent sampling indicates that brominated flame retardants (PBDEs) are also higher in Puget Sound herring and are rapidly increasing in the marine food web in general.
- Male English sole exhibit signs of feminization in nearshore habitats that receive untreated sewage effluent from combined sewer overflows, reflecting the ability of stormwater to transfer pollutants.

The effects of toxic contaminants remain the focus of considerable research. What is already clear is that these substances are causes for concern and that activities occurring now will have repercussions to the Puget Sound food web and the health of many species—including humans-- for decades.

End Box

Pathogens that have received the most extensive study in marine species are those that occur in artificial propagation settings, such as the bacteria and viruses affecting salmonids. For example, *Renibacterium salmoninarum*, the causal agent of Bacterial Kidney Disease (BKD), is endemic in many salmonid populations and is a significant cause of mortality in hatcheries and captive broodstock programs for ESA-listed salmon stocks. There currently are no completely efficacious vaccines or therapeutics to control BKD, and breaking the cycle of infection is exacerbated by the fact that the pathogen can be transmitted from the adult female into her eggs. Another pathogen affecting salmonids is infectious hematopoetic necrosis virus (IHNV). This virus readily infects fry and small fingerlings during the freshwater life stage, where mortality can reach 100%. Fish that survive can become carriers, capable of transmitting the virus to other fish through feces, urine, and external mucus. In both of these examples, studies continue on the potential for transmission of the pathogens from hatchery to wild stocks, as well as on methods to control their respective diseases.

3.6.3.2 Pathogen transfer and human health

An example of the interconnectedness of human actions and other species is the relationship between oceans and human health (box _____.) Human activities may release pathogens (bacteria, viruses, and parasites) into the marine environment through inadequate sanitation practices, with the potential to directly infect humans during recreational use of contaminate beaches, directly infect marine mammals and contaminate fish and shellfish. The release of antibiotics and antimicrobial resistant bacteria into the environment can also form a reservoir for transmission of antimicrobial resistance to pathogenic bacteria making them more difficult to treat in clinical settings. Moreover, naturally occurring marine bacteria such as members of the *Vibrio* genus can accumulate in shellfish, crustaceans, and fish, and can cause significant disease through ingestion of raw or undercooked seafood, or through contamination of wounds.

Changes to ecosystem processes such as nutrient availability and temperature regimes further influence the potential for amplification of infectious pathogens and subsequently transmission of infectious diseases to humans and other species. The full valuation of a particular ecosystem service, such as water purification and waste treatment, must consider all of the linkages to species, habitats and physical/chemical processes throughout the system.

Oceans and Human Health

Human health is unequivocally linked with the oceans. In a broad sense, ocean health impacts human health just as human activity impacts ocean health. Current pathways by which ocean factors affect human health include transmission of infectious disease, as well as exposure to marine biotoxins and chemical contaminants. For example, a variety of naturally occurring pathogens exist in the marine environment in fish and shellfish that are capable of causing human disease. In the U.S., the majority of seafood-related, bacterial infections in humans are due to two members of the *Vibrio* species, *Vibrio vulnificus* and *Vibrio parahaemolyticus*. Bacteria shed in animal feces are a major cause of gastrointestinal disease acquired by the ingestion of contaminated food or drinking water by animals and humans. In the United States, there are approximately 1 million cases of campylobacteriosis with ~100 fatalities, and approximately 40,000 cases of salmonellosis, annually. In addition, there are approximately 25,000 cases of foodborne disease that require hospitalization every year. Many pathogens present in estuaries and oceans are the direct and indirect result of human activities, including poor sanitation, inadequate water treatment practices, and agricultural run off. Such infectious bacteria and viruses also have the capability to infect marine species that become carriers of these pathogens. Infectious bacteria often possess genes conferring resistance to antimicrobial compounds, and form a reservoir for transfer of these genes to human pathogens

Importantly, the oceans may also provide clues about current and potential impacts to public health through examination of how toxins and pathogens affect marine fish and shellfish. Sentinel species can serve as important indicators of the status and trends in ocean health, and the observation and study of appropriate marine organisms can lead to a better understanding of potential public health risks.

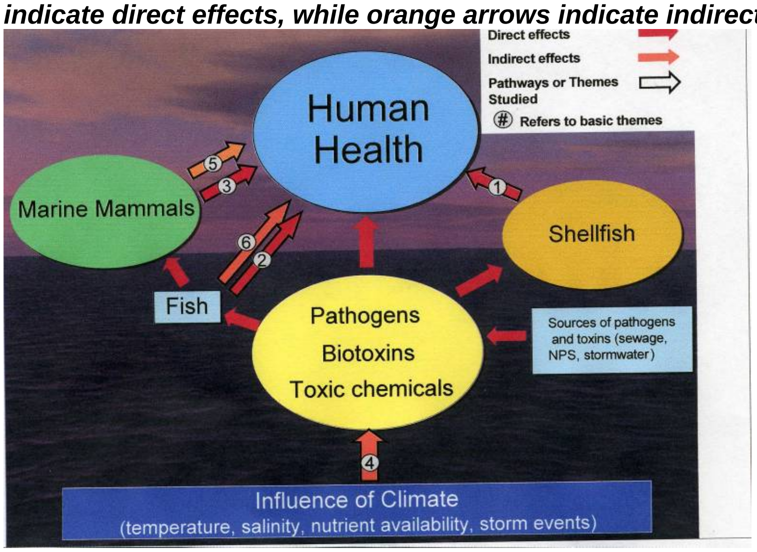
<u>Direct human health effects:</u>

- Human disease risk as a function of exposure to shellfish contaminated with pathogens and marine biotoxins.
- Finfish and shellfish as vectors for pathogens and substances toxic to humans.
- Impact of microbial disease on marine mammals and potential risk of direct disease transmission from marine mammals to humans.

<u>Indirect human health effects:</u>

- Role of climate in amplifying pathogens and marine biotoxins and altering inputs of toxic substances and pathogens to marine ecosystems.
- Marine mammals may be sentinels of existing or “emerging” human pathogens in marine ecosystems, or of the effects of anthropogenic and natural stressors on human health
- Using fish as a model to determine effects of anthropogenic stress on disease transmission dynamics.

Figure : A conceptual model for oceans and human health, illustrating the direct and indirect pathways of pathogen and toxin transmission from the oceans to humans. Red arrows indicate direct effects, while orange arrows indicate indirect effects.



3.7 Humans and Ecosystem Change

HUMAN ACTIONS
-- resource extraction -- water diversions --
shoreline development – pavement
transportation infrastructure --
-- introduction of non-native species --
-- introduction of contaminants --
-- accelerated nutrient loading --
-- recreational activities --

Early residents of Puget Sound inhabited a much different ecosystem--a projectile found in a mastodon rib near Sequim signifies the ever-changing nature of climate, species and habitat. Humans have clearly been an integral part of the Puget Sound ecosystem for millennia, but in the last two centuries the pace and magnitude of resource utilization has changed dramatically. Although we think of impacts to Puget Sound as recent, many resource extraction and construction activities that were initiated in the 1800s have altered ecosystem processes in ways that continue to affect Puget Sound today (figure ____ timeline).

As humans have expanded their footprint on this landscape, we have increasingly become drivers of ecosystem change. While much of the terrestrial area draining into Puget Sound is still forested, the structure and composition of the forest is much different than it was when 18th century European explorers arrived. Timber harvest, extensive pavement, dams and dikes have altered freshwater and sediment transport processes between terrestrial and marine landscapes. Fully one-third of the shoreline in Puget Sound is estimated to have been modified by humans, further interrupting the processes that move sediment and nourish beaches and vegetation along the nearshore (PSWQAT, *Puget Sound Update 2002)*. The alteration of these ecosystem processes has changed the quantity, quality and connectivity of habitat for numerous species of marine organisms and reduced the ability of the ecosystem to meter peak flows, deliver nutrients, absorb waste and provide other services.

Puget Sound urban centers are poised for expansion, and are located along shorelines and bays where their impacts to the marine environment are the most immediate. Since the 1800s, it is estimated that Puget Sound has lost 73% of its salt marsh habitat, primarily due to urbanization (PSAT 2005, *State of the Sound).* Many patches of marine and freshwater habitat have become too fragmented for migratory species to use. Intentional and accidental introductions of non-indigenous species have affected the composition and abundance of native species that once thrived in Puget Sound. Large scale harvest of salmon, depletion of top level predators such as *Orcas*, and active farming of oysters and other shellfish have further affected native species abundance with likely impacts to prey organisms and the food web.

ECOSYSTEM SERVICES

- Provisioning Services: salmon, shellfish, timber, water supply
- Regulating Services: waste purification, disease control, storm protection
- Cultural Services: spiritual, aesthetic, recreational
- Supporting Services: Nutrient cycling, habitat formation, biodiversity

Humans have benefited directly from the high productivity of Puget Sound as users of timber, fish, shellfish, water, fertile soil, transportation corridors, eco-tourism, and other ecosystem services. However as some ecosystem services have expanded (transportation, waste treatment, water supply) others have declined (shellfish growing areas, populations of forage fish and marine birds). Assessing Puget Sound in terms of its provision of ecosystem services requires specific measures that can be used as a common currency for evaluating tradeoffs and adapting strategies over time. The development of such measures is complicated, but is being attempted in many cases with existing science. A clear and transparent decision framework can organize what is known about both the natural and socio-economic systems and highlight the choices for the benefit of future scientists and policy-makers. More information on the integration of natural and social sciences in developing decision frameworks is contained in Section 4.

People living in the region are attentive to the expansion of the human role in the Puget Sound ecosystem and have supported steps to protect ecosystem health for several decades. Large scale actions such as the effort to eliminate the disposal of sewage into Lake Washington (box ____) have occurred largely in response to scientific input and a motivated public. The Puget Sound Action Team reports on a series of actions being implemented to remediate and prevent further habitat damage. Key accomplishments have included the cleanup of hundreds of acres of contaminated sediments and shellfish growing areas, removal of invasive *Spartina*, and assistance to communities in protecting forage fish habitat and preventing oil spills (PSAT, 2005).

The Rescue of Lake Washington: Melding Scientific Research and Public Action

Insert a drawing or photo of Lake WA

In the 1950s, an estimated 20 million gallons per day of sewage effluent entered Lake Washington from Seattle and other communities surrounding the Lake. The discovery of the cyanobacteria *Oscillatoria rubescens* in the Lake in 1955, and the implication that phosphorus from sewage effluent was acting as fertilizer for its production, led to predictions by UW Zoology professor W.T. Edmondson and other scientists that nuisance algal conditions and water quality deterioration would worsen in the future. Although the Lake was already visibly impaired, it had not yet deteriorated seriously, and the call for public action led to the creation of Metro in 1958. Between 1963 and 1968, over 100 miles of sewer trunk lines and interceptors were laid to carry sewage to treatment plants, and effluent entering the Lake was reduced to zero in February, 1968. The $140 million project, considered the costliest pollution control program in the country at that time, was completely locally financed.

The transparency of Lake Washington responded quickly, improving from only 30 inches in 1964 to a depth of 10 feet in 1968. The elimination of the phosphorus load from effluent set off a complex chain reaction of species responses, beginning with the decline of *Oscillatoria.* The water flea *(Daphnia)* is a filter-feeding crustacean that had been suppressed by *Oscillatoria* because it clogs the filter apparatus. The decline of *Oscillatoria* led to an improvement in conditions for *Daphnia*. *Daphnia* had also been suppressed by its predator--the possum shrimp *(Neomysis Mercedis)*. Improvements to spawning habitat in the Cedar River led to increases in long-fin smelt *(Spirinchus thaleichthys)*, a predator on *Neomysis*. The combination of these conditions allowed populations of *Daphnia* to increase and the *Daphnia* preyed on algal species, further improving the Lake's transparency to depths of 17 to 20 feet after 1976. A maximum depth of nearly 25 feet was recorded in 1993.

The application of scientific information to public action and the successful rescue of Lake Washington from deterioration has been the focus of follow-up research by natural and social scientists for decades, and is internationally known.

"If you explain it well enough, people will do the right thing."

--- quote recollected by W.T. Edmondson following the vote to create Metro in 1958 (Edmondson, 1991)

Significant efforts to protect and restore terrestrial and freshwater habitats in the Puget Sound region also are underway. The Puget Sound Salmon Recovery Plan summarizes many of these actions and their anticipated benefits to watersheds and the fish (Shared Strategy 2005). Major focal areas of attention include restoration of estuarine and river floodplain habitats through dike and levee setbacks, regulation of forest practices such as road-building and harvest schedules, protection of ecologically intact habitats through acquisition, incentives, and regulation, and barrier removals designed to improve natural stream flows and movement of fish, sediments, and nutrients throughout watersheds.

Fisheries harvest levels have always been difficult to assess as a measure of ecosystem function as fish populations respond to multiple, interacting and unpredictable ecosystem dynamics. However, harvest management forums for Pacific salmon and groundfish are attempting to incorporate a broader look at ecosystem services in the development of long term management plans. Sophisticated modeling tools are being developed that look at multiple species, predator-prey abundance, and the spatial distribution of the fishers themselves. The Puget Sound Salmon Recovery Plan (Shared Strategy, 2005) highlights the relationship of the three H factors for salmon -- habitat, harvest and hatcheries, and the importance of integrating these factors during recovery and ongoing management (box ___).

The Shared Strategy Recovery Plan for Puget Sound Salmon: Connecting Human Communities and Salmon Recovery

Insert a photo of the recovery plan cover or a Chinook. Or a thumbnail for each of the H factors.

Following the listing of Puget Sound Chinook and other salmon as threatened species in 1998-99, a coalition of federal, state, tribal, and local governmental leaders and salmon recovery organizations formed the Shared Strategy for Puget Sound to prepare a recovery plan that would be prepared by the communities that would be committed to its implementation. Within the plan, the factors affecting salmon and the actions needed for recovery were largely organized around the "H's" of salmon management: Harvest, Hatcheries, and Habitat.

Habitat: The communities of Puget Sound were asked to evaluate habitat conditions within each watershed, assess the capability of their river system and nearshore areas to form and sustain habitat, and identify a suite of actions that would cumulatively lead to recovery. The need for suitable habitat for spawning, foraging, resting, hiding from predators and feeding throughout the salmon's complex life cycle was considered in scientific and community discussions in the 14 watershed planning areas described in the plan. Specific strategies designed to protect and restore sufficient habitat to recover salmon are outlined in each watershed plan.

Hatcheries: The decline of salmon during the 20th century led to the increased use of artificial propagation to compensate for dwindling returns. Although hatcheries can be used as a tool in the recovery process and provide opportunities for harvest, their operations can create risks with respect to the loss of genetic diversity, domestication, disease transfer and competition with wild populations. The salmon recovery plan describes ongoing actions by state, tribal and federal managers of hatchery facilities to minimize risks, and integrate hatchery operations with harvest plans and habitat restoration.

Harvest: Fishing for salmon in Puget Sound is structured around the cultural, legal and economic history of the Puget Sound region, international agreements, and the biological patterns of the species' life histories. The co-managers of salmon in Puget Sound, consisting of the treaty Indian tribes and the State of Washington, have developed a comprehensive harvest management plan that describes how they will constrain harvest as recovery proceeds.

The Puget Sound Salmon Recovery Plan is available online at www.sharedsalmonstrategy.org.

In addition to these efforts, many scientists and resource managers in the Puget Sound community are looking at fundamental ecosystem processes that will affect human well-being in the future. Potential and anticipated changes to climate, pathogen distribution, habitats and food web dynamics require analysis and action on a Sound-wide basis. Some groups, such as King and Snohomish Counties and their cities, already have begun to explore the impacts of future climate conditions on water supply. Further, businesses, policy makers and local communities will need tools to address ecosystem services across the entire range of values and tradeoffs.

In Section 4, groups of social and natural scientists report on possible futures for Puget Sound– how the Puget Sound ecosystem may respond to changing conditions and actions, and likely shifts in ecosystem services as a result of natural and human-induced changes. Additionally, Section 4 includes a presentation of tools for decision makers to use in implementing a system-wide view--considering linkages and tradeoffs toward sustainable ecosystem management.

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VALUES/HUMAN WELL-BEING

Human health, cultural heritage, biodiversity, recreational and aesthetic enjoyment.

The Puget Sound Ecosystem: Milestones of Two+ Centuries of Change

Fishing, Hunting and gathering

Photos or sketches on this side?

Exploration and fur trade

Early Timber harvest or mill

Early aquaculture

Clearing and diking for establishment of farmland.

Railroad construction along shorelines.

Pre-1790	Tribes develop religious, economic and cultural societies oriented around salmon, cedar and other indigenous natural resources.
1792	Vancouver sails into Puget Sound. Human population estimated at 50,000
1810-40	Fur trapping depletes beaver populations, a keystone species of habitat formation.
	Small pox and other diseases wipe out three-quarters of the native human population.
1847-64	California gold rush increases demand for Olympia oysters and other seafood.
	Small, local mills are constructed to supply building materials for settlers, and expand to meet the demand for the gold rush and ship building. Easy timber along marine and lower river shorelines is harvested first.
1854-5	Tribal treaties signed.
1863	First dike constructed in Skagit County on LaConner flats for development of agricultural land.
1874	Pacific oysters introduced due to depletion of Native Olympia oyster.
1877	Puget Sound's first fish cannery built at Mukilteo.
1883	William Renton notes that "timber contiguous to the Sound is nearly exhausted"
1883-91	Transcontinental railroad connections to Tacoma, Seattle and other cities completed, increasing the ability to market timber. Railroads are constructed along Puget Sound shorelines and river basins, and to access timber.
1889	Washington becomes a state.
1896	First Puget Sound salmon hatchery constructed on the Baker River
1896	First agricultural irrigation system in the Dungeness valley.

1900 Port Blakely in Kitsap County is the location of the largest lumber mills in the world. Technological advances such as the band saw and steam donkey boost lumber production.

Dams

1900-10 Seattle population expands from 81,000 to 237,000 due to Alaska Gold Rush.

1900-20 Several major dams constructed on the Cedar, Nisqually, White, Elwha and other rivers for urban water supplies and to power mills.

White, Cedar and Black rivers are re-routed.

Denny Regrade

1903-11 Peak period of the Denny Regrade: 16 million cubic yards were removed from Seattle hills, mostly by water blasting. About half of the spoils were deposited in the tideflats, forming Harbor Island.

1906 Puyallup levees constructed.

1913 Peak cannery pack in Puget Sound with 2,583,463 cases of Pacific salmon.

Construction of Ballard Locks

1913-27 Puget Sound salmon hatcheries import eggs from the Columbia River.

1916 Ballard Locks completed, dropping level of Lake Washington by approximately 9 feet and eliminating substantial marsh habitat.

Expansion of Manufacturing – aviation and ship building.

1916-18 Puget Sound Naval Shipyard undertakes major production of military ships during WWI.

1917 Boeing Airplane Company is incorporated.

1920s Highway 101 constructed along the west side of Hood Canal, crossing all major river deltas.

Dams built on Skokomish and Skagit systems.

Old hatchery photo

1924 Manila clams introduced with shipments of Pacific oyster seed.

1926 All time peak of Washington lumber production at 7.5 billion board feet.

1927-57 One hatchery in the Green River is the source for 67.7% of Chinook releases throughout Puget Sound.

	1941	*Spartina alterniflora* intentionally planted in Padilla Bay by a hunting club.
	1942-5	Puget Sound is major center for manufacturing and military staging during WWII.
Expansion of transportation network – roads and bridges	**1945-60**	Major expansion of transportation infrastructure in Puget Sound including Interstate 5
	1950s	Recreational fisheries expand following World War II. Recreational catch of Chinook in Puget Sound in 1957 estimated at 238,000.
Recreational fisheries		Cold war era boosts Boeing production.
		First oil refinery built on Puget Sound.
		According to a federal report, Puget Sound is the sixth most polluted area in the country.
	1960s	Flooding leads to expansion of levee systems along Cedar, Sammamish and other rivers.
Dikes	**1962**	Howard Hanson Dam constructed – Green R.
	1968	Sewage effluent entering Lake Washington, once estimated at 20 million gallons per day, is reduced to zero.
	1970s	Peak contaminant levels in Puget Sound sediments. The manufacture of PCBs and several other toxic contaminants are banned nationally.
		Construction of numerous bulkheads, docks, piers and revetments along central Puget Sound basin.
Construction of bulkheads, docks and piers	**1971**	Shoreline Management Act is approved.
	1974	Boldt Decision determines that treaty tribes in WA reserved the right to harvest up to 50% of the salmon catch.
	1977	Seattle is the second busiest container port in the U.S. and sixth busiest in the world.
Software industry expands.	**1981**	Industry giant IBM selects tiny Microsoft's MS-DOS as the operating system for their new personal computer.
	1985	Pacific Salmon Treaty signed with Canada.

1999	Endangered Species Act listing of Puget Sound Chinook is the first major listing affecting an urban area. Draft recovery plan completed in 2005.
2000	Human population of Puget Sound estimated at 3.8 million
2005	Southern resident orca population listed as endangered.
2020	An additional 1.4 residents expected, bringing the combined total of Puget Sound and the Georgia Basin to over 7 million.

Section 4: The Future of Puget Sound

(*To be completed*) *This section is intended to consist of a series of papers on issues that have surfaced as primary drivers of change to the future of the Puget Sound ecosystem. . Each paper would be completed by a few scientists from the relevant field of expertise, and would be approximately 5 - 6 pages long. The outlines below are draft—it will be the authors' prerogative to modify the content as appropriate, and in consultation with the other authors of this document. Drafts to be available August 8.*
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The introduction to this section would indicate that the issues below have surfaced as the primary drivers of change to the Puget Sound ecosystem and the services it provides.

Where possible, each issue should include the following:

- *Relationship to the conceptual figure on ecosystem wide approach (Fig 2-1) and which pieces are being illustrated.*
- *Boxes that describe linkages among issues.*
- *Answers to the following questions:*
  What conditions have changed; what are the trends?
  What changes and consequences are anticipated in the next 2 to 4 decades?
  How do these changes relate to our use of and interaction with the Puget Sound ecosystem as a whole?
  What are the major gaps and uncertainties in our scientific knowledge?

4.1 <u>Climate Change and the Puget Sound Ecosystem:</u> Likely changes to climate in the Puget Sound region and consequences for the ecosystem.
- Brief overview of the CIG report on PS climate impacts and implications.
- Possible topics to cover:
- How changes in physical characteristics – water temperature, precipitation (freshwater inputs), water quality – might change species and habitat distributions and therefore change goods and services (e.g. primary physical changes; increases in peak flows, reduced low flows, sea level rise, changes in services and potential tradeoffs).
  - Changes in environmental conditions and thus food web changes – non-indigenous species, pathogens, etc.
  - Potential effects on water supply
- What do we know about ocean condition changes due to climate change and the effects of ocean conditions on PS? E.g. changes in salinity, temperature, and thus nutrients, etc.
- What are the potential effects of future climate on protection and restoration efforts in Puget Sound? (Box--Snohomish climate/ land use and restoration strategies?)
- Describe briefly how land use planning or other actions interact with potential changes resulting from climate
- Key informational gaps and uncertainties.

4.2 Forming and Maintaining Habitats: Description of trends in habitat quality and quantity in Puget Sound, causes and consequences of that change.

- Trends in habitat distribution, area and quality in Puget Sound.
- What has caused these changes in habitat? What are the changes to relevant processes that form and maintain habitat?
- How do human modifications of, and interaction with, habitats affect ecosystem goods and services?
  - o Include 2-3 substantial and important examples (e.g. shoreline modification to eelgrass to herring to salmon to orca to whale watching).
  - o Include water quality impacts from stormwater, other freshwater and atmospheric sources.
  - o Include a box describing Hood Canal DO as example of changes in pelagic habitat condition, and how the work there is to decipher the primary causes of that change.
- Key informational gaps and uncertainties.

4.3 Species and their Interactions: Top Down and Bottom Up Changes

- Trends in species abundance, both native and introduced
- Human interaction with food webs and consequences.
  - o Reductions in top-level predators (non-human) and resulting changes in other species and ecosystem services (refer to eco-tourism industries such as whale watching, kayaking, birding; also fishing)
  - o Changes to species abundance and composition resulting from aquaculture, harvest. Tradeoffs in benefits to humans and costs to local species, benthic and pelagic habitats and the ecosystem services they provide.
  - o Changes to ecosystem processes, such as nutrients and temperature and bottom-up impacts to species
- A case-study or example
- Key informational gaps and uncertainties
- Relationship to recovery strategies and ecosystem services.
  - o Protection and/or recovery efforts that are focused on top-level predators that consider prey, competitors, predator and habitat needs are likely to be more successful.
  - o Recovery strategies that consider human uses and interactions with the ecosystem, e.g. land use, harvest, input of contaminants will be more successful.
  - o Relative effectiveness of multi-species management strategies that incorporate interaction with habitats, predators, prey and pathogens in achieving sustainable harvest.

4.4 Interactions between Natural and Human Systems in Puget Sound

Information about the relationship between natural, human systems is key to estimating ecosystem responses to alternative management approaches.

Potential changes in human population growth and distribution across the landscape, and how these changes might interact with the rest of the ecosystem.

- Relationship to recovery strategies and ecosystem services.
- Patterns of human population growth (past and potential future)
- Effects of human behaviors as drivers of land use and marine water uses
- Effects of different land uses on ecosystem attributes (or ecosystem goods).
- Box – interactions between humans and ecosystem elements. (Use an example such as transportation needs and potential for marine zoning as a tool. Effects of different land uses on ecosystem attributes (or ecosystem goods).
- Alternative incentives and management approaches based on social science input.
- Connectivity and feedbacks between human and natural systems, alternative future scenarios, and implications for management.
- Key informational gaps and uncertainties.

4.5 Human Health and Well-being: The ways in which the Puget Sound ecosystem affects human wellness (physical, cultural, mental, etc.), and how changes to the ecosystem affect us directly (some of our goods and services). In each category describe how alternative futures could improve or worsen these situations.

- Human health: Trends, changes and potential consequences
  - Trends in contaminants (nutrients, pathogens and toxins) in the environment and in species. (Note that species can be useful sentinels for human health, such as migratory birds and bird flu.)
  - Effect on food sources and habitat for humans (swimming, living, etc.)
  - Toxins: Anthropogenic (PCBs, PBDEs, etc.), Biological (HABs)
  - Disease and pathogens
- Quality of life
  - Recreation and leisure
  - Tourism
  - Locations/species of cultural significance
- Thus human uses of and interactions with the ecosystem cause changes in ecosystem elements and thereby impact our health.
- Discuss alternative future scenarios—under different management implications associated with this issue.
- Key informational gaps and uncertainties related to human health, e.g., persistence of toxins, the need to quantify total contaminant loading in Puget Sound

4.6 Integrating the Sciences: Natural and Social Science Support for Decision-Making: Decision frameworks and how they can help organize existing information to support decisions now and help focus/prioritize monitoring and future research needs. Decision frameworks allow evaluation of tradeoffs, identification of key science gaps, and allow decision-making that will account for uncertain futures.

- Social Science: Connection between social science information and how it can be integrated into decision-making.
  - e.g. likely outcomes of alternative incentives on ecosystem goods or attributes; costs of alternative actions producing similar results
  - drivers of human behavior and connection to feedback with natural drivers
- Natural Science: Connection between scientific information and how it can be integrated into decision-making processes.
  - e.g. likely outcomes on multiple ecosystem goods from a single ecosystem change or management strategy.
- Use of conceptual and quantitative decision support systems in decision-making on an ecosystem-wide level
  - Focusing on goals (human values) and using conceptual or quantitative models to help identify and weigh trade-offs and to choose between options.
  - Identify key information gaps that affect ability to make decisions.
- Ecosystem governance
  - How can science and policy interact more effectively to inform management in Puget Sound?
  - What is the existing structure of ecosystem management, how effective is it, and what are alternatives for the future?
  - [This section could end up as a series of questions directed to the partnership]

Draft: Final revisions will be made as the issue papers are developed. These are intended to flow from both sections 3 and 4.

Key Findings for the Future of Puget Sound

> *To achieve and maintain healthy ecosystems requires that we change our perspective….* (Pew Oceans Commission, 2003)

Scientists resoundingly agree that an ecosystem-wide perspective is essential to insure that a healthy and viable Puget Sound will remain as the legacy for future generations. Understanding the interactions and linkages among species, habitats, and the processes that support them is critical to our ability to predict the response of the ecosystem to natural perturbations and management actions. Humans have been an integral part of the Puget Sound ecosystem for millennia, and have now become one of the driving forces of ecosystem change. Thus the integration of information about human and natural systems is vital in analyzing alternative management approaches.

The Puget Sound ecosystem exhibits several indicators of severe degradation such as listed species, a fragile food web, diminishing habitats, and persistent and toxic contaminants. Scientists stress the importance of concerted and immediate action that will allow the Puget Sound region to take advantage of opportunities to halt or reverse continued declines. Furthermore, preventative strategies are one of the most ecologically and cost effective solutions for the future. While change is an inherent feature of any ecosystem, the projected changes in climate, population growth, and the complexity of Puget Sound all point to the need for a broader outlook for ecosystem management.

1. An ecosystem-wide view of Puget Sound will improve our ability to choose cost-effective actions and predict long term results.

- Cumulative pressures on terrestrial, freshwater and marine processes have widespread, interactive, and long-term impacts across the species and habitats of Puget Sound. Regional and local decisions that are made in the context of the connections and tradeoffs among Puget Sound ecosystem goods and services will increase the likelihood that the ecosystem can be managed in a sustainable way.

- An ecosystem-wide framework can be used to identify human and ecosystem linkages and assist policy-makers with the choice of cost-effective management actions. Expansion of modeling tools beyond single-species forecasts has recently advanced and may be useful for land-use planning, marine zoning, and other management decisions.

- An ecosystem-wide perspective can help us understand *why* Puget Sound's water quality, water quantity, species and habitats respond the way they do to existing management activities. Understanding how ecosystem processes such as nutrient loading, freshwater input, marine circulation and climate interact and are connected to upland management will help identify solutions. (Lake WA example)

- Monitoring strategies that assess connections, cumulative changes to ecosystem components and their interactions will allow measures of progress towards ecosystem goals. (For example, managers may be able to predict and monitor how the combination of salmon harvest levels, shoreline armoring, the availability of spawning sites for herring and other forage fish, and oceanographic conditions will affect the presence and quantity of other species such as Orcas and marine bird populations.)
- An ecosystem-wide perspective that includes estimating future human actions, and evaluating likely resultant ecosystem goods and services allows managers, elected officials and the public to explicitly weigh potential tradeoffs in alternative management strategies. This allows for more transparent and informed decision-making, with greater likelihood of reaching societal goals.

2 Freshwater tributaries and marine receiving waters are under stress, which is likely to be exacerbated by future climate impacts.

2.1 Future climate impacts in the region are likely to result in reduced summer freshwater flows, increased winter peak flows and warmer stream temperatures.

- Seasonal and year-round freshwater quantity has already been identified as a factor impairing several threatened species in Puget Sound lakes, rivers, and nearshore environments (e.g. Shared Strategy, 2005). A number of other ecosystem services including domestic/ municipal/ agricultural water supplies and recreation are also affected by low stream flows. Improved water use efficiency through conservation, re-use or storage will help moderate the potential negative impacts of climate change on Puget Sound species, habitats and ecosystem services.
- The range of introduced species, including novel pathogens, that is able to flourish in the Puget Sound region may change as a result of these physical changes. The range of native species may also be affected, particularly for those located at the southern end of their range that cannot tolerate increased stream temperatures and changing flow regimes.

2.2 Future climate impacts in the region are likely to result in sea level rise in Puget Sound—increases in sea level could be up to 1 meter higher in South Puget Sound within the next 100 years.

- Current and future uses of low-lying areas could be compromised and could affect the quality, quantity and functioning of nearshore, estuarine and lower river habitats.

- Rising sea levels may be beyond the control of Puget Sound decision-makers. However, land use plans and protection and restoration strategies can take into account possible increases in sea level for nearshore, estuarine and lower river habitats as well as commercial, residential and municipal development.
- Zoning, land use and protection (e.g. marine reserves) strategies that consider the likely future distribution and abundance and habitats will have greater long-term success than those that do not.

3 Projected increases in human population growth in the Puget Sound region will increase pressure on ecosystem goods and services.

3.1 Shoreline modifications are already extensive enough in the main Puget Sound basin that the natural habitat-forming processes have been disrupted, and the distribution of habitat types has been affected. (PSNERP--)

- The pattern and extent of shoreline hardening and other modifications throughout the Sound affect the success of strategies to protect and recover beaches, eelgrass habitats, kelp forests, and natural shorelines.
- Analysis of the effects of development activities using quantitative or conceptual models can assist decision-makers in assessing broader, cumulative impacts to the Puget Sound ecosystem.

3.2 Focusing shoreline and upland development and other land uses into strategic locations in Puget Sound can allow achievement of a diversity of ecosystem services that are consistent with ecosystem goals.

- The loss of salt marsh and other important habitat types has been regionally significant in Puget Sound and severe in specific areas. Habitat forming processes such as beach nourishment and bank stabilization, and the maintenance of eelgrass and kelp habitats require an ecosystem-wide approach for planning, protection and restoration to insure diversity and connectivity of habitats. (For example, spawning areas for forage fish in Puget Sound are now largely concentrated into two or three counties, such as Island County, and land use decisions in those locations will affect ecosystem services throughout the Sound.)

- Land conversions from timber and agriculture and associated urbanization impacts are increasing throughout the Sound. While some land use planning and regulatory efforts are having positive effects on species, habitats, and services, these remain largely small scale and localized. Achieving desired ecosystem services for an increasing human population in Puget Sound is possible with explicit balancing of alternative land uses and careful attention to the locations of impacts and uses.

- Strategies that allow agriculture and healthy ecosystems to co-exist will help to alleviate impacts associated with urbanization.

3.3 Contaminants—toxins, nutrients, pharmaceuticals and pathogens-- entering Puget Sound accumulate in sediments, marine waters and organisms and negatively impact biological populations, ecosystem integrity, harvest availability, and human health.

- Stormwater runoff in Puget Sound is causing water quantity and quality problems. Indicators such as impervious surface cover and contamination of fish are increasing (PSAT, 2005). Peak flows also alter habitat formation in urban and rural river systems. Strategies to reduce the magnitude of stormwater runoff events or the toxics and excess nutrients they deliver during winter high flows could reduce their negative impacts on the health of commercially, recreationally and ecologically important species like shellfish.

- Toxins introduced into Puget Sound lands and waters are showing up as high concentrations in upper-level predators such as salmon, seals and orcas, even though some of these substances were banned decades ago. The number of acres of highly contaminated sediments in Puget Sound has been reduced due to clean-up efforts. However, contaminants such as Polychlorinated Biphenyls are declining slowly, if at all, and levels of Polycyclic Aromatic Hydrocarbons have increased in long-term sediment monitoring stations in Puget Sound (PSAT, 2005). Reduction of inputs of toxic compounds to the Sound will benefit ecosystem and human health overall.
- Quantification of rates and amounts of toxic substances entering Puget Sound can be used to assess sources and deposition Sound-wide.
- Remediation and restoration actions designed to clean up specific locations where "legacy" toxics are concentrated can help to reduce the amount of toxins that move back into the food web.

- Human population growth has the potential to result in greater levels of pathogens, pharmaceuticals, chemical toxins and nutrients being discharged into freshwaters and the Puget Sound.

- Artificially high levels of nutrients, introduced through agriculture, stormwater or septic tank drain off can affect the primary productivity of the system locally or regionally, leading to non-normative blooms of algae.

- Pathogens

3.4 Human population growth is likely to result in increased demands for freshwater in general and potable water in particular.

- Implementation of actions that affect water quality and quantity that considers this likely population growth should have smaller long-term impacts than those that do not.

4. It is likely that Puget Sound's food web has been substantially altered but the nature and strength of interactions among species in Puget Sound food webs is not well understood.

4.1 The focus on single "iconic" top level predator species such as Puget Sound Chinook and Orcas is beneficial for energizing public awareness of ecosystem issues. However, considering competition among predator species and the value of detrital, benthic and other so-called lower trophic organisms in maintaining the food web is essential in developing sustainable recovery strategies.

- Efforts to recover top-level predators like birds and whales will benefit from concurrent actions aimed at recovering their food items and other species within the food web.
- Management strategies designed to recover populations of top level predators like orcas, sea otters, bald eagles and salmon can conflict unless impacts to other predator, competitor, and prey species are considered.

4.2 Life history details such as where species live during some life stages, what they eat, and how long they live are not well known for many marine species in Puget Sound.

- Collecting basic life history information will benefit species recovery and improve our ability to estimate ecosystem responses to diverse types of management actions such as modifying harvest levels or decisions about where to permit construction of private docks.

4.3 Despite their foundation at the base of the food web, we have a poor understanding of phytoplankton and zooplankton populations in Puget Sound and how they respond to environmental conditions.

- Actions designed to improve water quality or reduce shellfish contamination problems that include hypothesized effects of plankton communities on nutrient and toxics cycling are more likely to be successful.
- Modeling and understanding changes in the food web will benefit from a more complete understanding of plankton in the region.

4.4 Some economic sectors of Puget Sound, such as fishing, commercial and recreational shellfish harvest, aquaculture, and eco-tourism, are completely and directly dependent on ecosystem function and productivity, and in turn have immediate effects on ecosystem goods and services.

- Management incentives and consideration of where these activities occur can improve the chances that operations of resource-based sectors are sustainable and increase the chances that they can continue to benefit from the ecosystem in the face of an increasing human population.

- Addition and removal of substantial quantities of single species through harvest, hatchery and shellfish culture activities likely is having wide ramifications throughout the Puget Sound food web. Assessing the potential impacts of activities directly dependent on ecosystem function on other ecosystem elements (such as habitats and species) will improve the chances that multiple uses of the ecosystem will be supported.

- The introduction and expansion of invasive species in Puget Sound has the potential to severely disrupt the food webs or habitats on which these economic sectors depend.

5. Possible summary of research needs if not covered in body of document

In summary, the scientific community has emphasized a holistic ecosystem management approach that emphasizes connectivity among parts of the ecosystem. Such linkages take many forms including the relationship of fundamental drivers such as climate change to our ecosystem, the connection between upland and shoreline activities and the function of marine processes and habitats, and the complex web of species in Puget Sound and the potential implications of past and future perturbations. Finally, the connections between scientists and decision makers are considered to be crucial in achieving a broader perspective and sustainable strategy for the future of Puget Sound.

This section will also detail more specific research needs that can help inform effective management in the near-term.

To be added:
Glossary
References